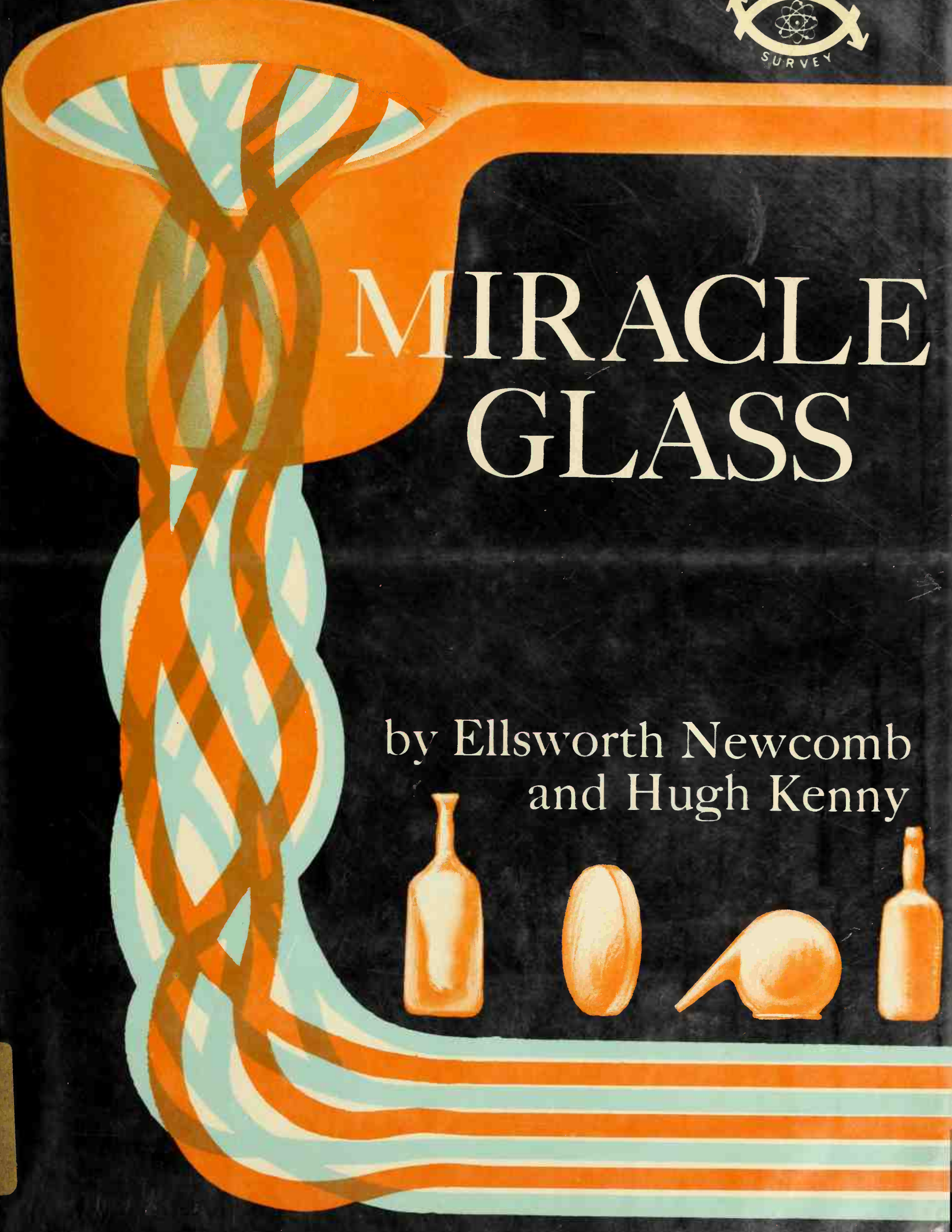
SCIENCE SURVEY

# MIRACLE GLASS

by Ellsworth Newcomb
and Hugh Kenny



# MIRACLE GLASS

by Ellsworth Newcomb
and Hugh Kenny

*illustrated by* Ayres Houghtelling

The first glass furnace was a volcano, its product a shiny black substance known as obsidian. No one knows exactly when man's own furnaces began to turn out the substance we know as glass, but artifacts have come down to us from Egyptian tombs, from Roman ruins, from Byzantine cities. The story of glass is told in stained glass windows, in Venetian mirrors, in modern skyscrapers.

Ellsworth Newcomb and Hugh Kenny, authors of Miracle Fabrics, Miracle Metals, and Miracle Plastics, now present a fascinating survey of the past, present and future of glass making. Using easy-reference charts, the authors show how the full possibilities of glass are only beginning to be exploited, and why one of man's oldest products stands today on the threshold of a golden age of new uses in art, science, and industry.

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# Miracle Glass

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*For our mother*
*Lucy Comstock Newcomb*

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MIRACLE PLASTICS
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MIRACLE METALS
  Illustrated by Robert Bartram
MIRACLE GLASS
  Illustrated by Ayres Houghtelling

# 1. Today's Wonder World of Glass

GLASS HAS MANY CENTURIES OF HISTORY AND adventure behind it. But today as we shall find, it is making a far more vital contribution to civilization than ever before. And it promises new wonders for tomorrow.

Objects of great beauty are created from it. But glass also serves as the material for numbers of essential everyday articles.

Glass can be as fragile as an eggshell, but a one-inch-square rod of it can be made strong enough to suspend a weight of 10,000 pounds. It can also be feather-light in one form and as heavy as iron in another.

Truly a miracle material, glass is so much a part of our homes, our schools, our cities, our way of life, that if it suddenly vanished, it would leave our world a huge disaster area.

Glass that was created by nature, not by man, is as ancient as the earth itself. It has been made by man for at least 3,500 years. In spite of its great age, though, in some forms in which it is now used, man-made glass is as new as if it had just appeared on the scene. What is more, experts tell us that this material, with characteristics unequaled by any other known substance, is only at the beginning of its career of usefulness.

In many ways glass is unique. It appears to be a solid, yet it has the same structure as a liquid.

Before we begin the strange story of glass, we had better make sure that we know just what solid and liquid mean.

Glass "appears to be a solid"—that is a substance that does not perceptibly flow. When we say that glass has the same structure as "liquid," we mean that as in all liquids, its smallest particles never assume the inflexible internal patterns of true solids.

Now we shall find out what we can about the very earliest glass we know about—glass that was made not by man, but by nature. The first known glass was obsidian, one of the forms of natural glass that was created in the fierce heat of volcanoes in many different parts of the world. Weapons made of obsidian may have been used as early as 75000 B.C. There will be more about this material and other forms of natural glass in the next chapter.

The glass that is familiar to us all, man-made glass, is created by mixing inorganic substances (materials that are neither animal nor vegetable) such as sand, lime, and soda, and melting them at high temperature. When the hot syrup, or *melt*, cools quickly, it becomes rigid without forming crystals.

It was once thought that the first man-made glass was produced quite by accident in some sandy place in Mesopotamia or Egypt. Some held that it was found by potters who happened to create it while firing, or baking their clay wares. Others felt that sailors found the substance in the ashes of a very hot fire over which they had been cooking food, as Pliny, the first-century Roman naturalist, related in the often-repeated story. Modern scientists do not accept these tales. Yet they do not claim to know where or when and under what conditions men did first make glass. Some all-glass beads are said to date back to 2600 B.C. But some experts question this.

If we wish to speak only of vessels that are not partly but entirely made of glass, it is positively known that the Egyptians made such all-glass objects as long ago as 1580 B.C. Vessels of this kind were also made in Mesopotamia during the same period.

So the question of the origin of glass still baffles us; perhaps it always will.

One interesting and plausible theory about the discovery of glass is that it came about through the smelting of copper and lead ores, for glasslike slag is often produced when these metals are smelted. Slag is a combination of earthy matter contained in the ore and waste materials of the furnace. Since it is usually lighter than the metals being smelted, it floats on top of molten metal and is easily separated from it.

Copper was smelted in Asia Minor as far back as 3000 B.C. and possibly a little later on Cyprus (the island that gave the metal its original name of *cyprium*, later changed to *cuprum*). The red metal was also smelted on the Sinai Peninsula not far from the area now famous as the site of King Solomon's Mines.

By experimenting with glassy slags, the ancient copper workers may have produced a glass similar to the material we now know. The blue color of much early glass and glazes, created by the addition of copper to the raw materials, makes this theory seem reasonable, as it is well known that when copper reacts with other elements it often produces compounds that are blue.

A second theory is that glass came into being through the evolution of ceramics—a group of materials high in sand content that were coated with alkali (nonacid) glazes. These existed in Egypt earlier than 3000 B.C. and are not be confused with clay-bodied pottery, which will not usually take an alkali glaze.

The immediate forerunner of glass in the evolutionary sequence is the material now known as faïence (pronounced fy-ahnss). It was used mostly to make jewelry and other small pieces. The surface is transparent glass but its body is white and porous and consists of crystalline quartz grains. These grains are loosely bound together by a glasslike substance so that in proportion to empty space, there is only a little glass material. If their method had been modified, the Egyptian faïence workers, it would seem, could quite easily have produced true glass which is a substance without any crystalline grains whatever. You will read more about ancient faience in Chapter 2.

Although the origin of man-made glass remains a mystery, its discovery, wherever or however it happened, is one of the most important developments of all time.

We are certain that glass has been made for at least 3,500 years. The glass of these very early times, though, was quite different in appearance from the glass of today. It was seldom transparent, and rarely without color. To make colorless glass requires a special technique, and the decoloration process was unknown until much later. Glass was also, for a long time, so valuable that only the rich and powerful could own it, and they treasured it as if it were gold or a precious gem. Today, although costly art objects are often made of glass, much glass is so reasonable in price that it is within the reach of almost everyone.

We'll follow the adventure-filled and often dangerous trail of glassmaking in the pages to come. But first, here are some uses of glass today.

In a relatively short time, glass has changed the appearance of our cities. Ever since New York's Lever House started the trend in 1951, new buildings have been designed with more and more windows (many of them double-glazed insulating windows to guard against both heat and cold). The blue glass exterior of the United Nations' lofty Secretariat admits sunlight but shuts out most of the heat of the summer sun. One skyscraper has seven acres of glass that admits light into its sixty stories. Twenty miles of Pyrex-brand glass tubing form the walls of a bottle-shaped structure in Racine, Wisconsin.

"State-hop" as much as you like, you will find cities of glass from Maine to California and from Canada to Mexico. Not only are the windows made of glass, but glass brick and opaque glass facings often cover under-structures of ordinary building materials. Such glass is heavier than ordinary plate glass and the highly polished surfaces are waterproof, weatherproof and rustproof. A high gale won't break them. They won't warp or swell. There are many colors and varieties to choose from. These and other types, including beautiful stained glass, will be discussed in later chapters.

Factories, schools, theaters and office buildings frequently have exterior walls and partitions of glass blocks. Entire buildings are insulated with fiberglass or glass-foam panels that not only insulate against heat and cold but also trap sound.

New York's Lincoln Tunnel and many other structures today have ceilings of glass tile that are not affected by fumes, acids or continued cleaning. They supply a clean surface that reduces headlight glare. Public buildings sometimes have glass-tile corridor walls; this tile is excellent for sanitary walls in kitchens, baths, showers and food markets.

Churches, schools, stores, banks, hotels, office buildings, hospitals, libraries, apartment buildings, private homes, motels—every structure designed by today's architects glitters with smooth and shining glass to let sunlight in and keep out winter cold. Special glass can not only reduce entrance of summer heat, but can make it possible to air-condition buildings and control temperatures less expensively without sacrificing light.

In your own home, glass is a familiar friend from the moment you enter. The door itself may have windows or "lights" of glass and perhaps a glass doorknob, too. There may be a glass wall overlooking a patio or terrace. Window glass, of course, we take for granted. The window draperies are often of fiber glass. There are mirrors, glass-topped tables, vases, ashtrays, lighting fixtures, counter tops, cookware, tableware, food and beverage containers, glass bottles and jars for medicines and cosmetics. An up-to-date kitchen will contain many glass ceramics—a brand-new family of materials in which the housewife can cook, serve and even freeze food. Refrigerators, stoves, dishwashers and furnaces are insulated with fiber-glass materials. The china cabinets will probably have glass fronts as well as shelves of glass. Fiber-glass filters catch dust in air-conditioning systems. Today fiberglass and plastics are made into entire pieces of furniture, such as tables and chairs. Heat-tempered (toughened) glass is used to make fireplace screens, and another high heat-resistant glass is used for stove-top units.

All efficient artificial lighting requires glass. The source we know best is the incandescent lamp invented by Thomas Edison in 1889. To state it simply, this bulb that lights the world is a wire within a glass bottle. Today many improvements have been made on the original and there are countless varieties of it. Hundreds of millions of electric light bulbs are manufactured each year in many thousands of different shapes and sizes. There are tiny bulbs no larger than a grain of wheat, while others measure thirty-five inches in diameter and require 50,000 watts—enough power to light forty homes, each burning more than twelve 100-watt bulbs.

A new screw-in electric light bulb, made of space-age glass ceramic, is about to go on the market as this book is being written. Composed of an extra-hard material almost impervious to heat, it transmits more light per unit of electricity than any other bulb. Such bulbs will at first be used to light parking lots, streets and other public areas. But General Electric, original maker of the new bulb, predicts that someday it will be used in homes—in small sizes, of course.

Glass serves as an essential component in many of the tools of science, such as the microscope, telescope, camera, thermometer, spectroscope and X-ray machine, among many others. While most scientific instruments contain glass in some form, glass provides the principal material for virtually all laboratory apparatus, such as flasks, beakers, distilling apparatus, bottles, jars, test tubes, vials and tubing.

In countless forms, from eyeglass lenses to the 200-inch mirror in the Hale Observatory telescope on Mount Palomar, California (the world's largest reflector telescope), glass serves to help and enlighten man.

In so-called "hot" laboratories where radioactive substances are studied, high-density glass set into steel-framed windows stops dangerous gamma radiation and shields scientists.

Polio vaccine, one of the greatest discoveries of all time, is filtered through porous glass. Glass laboratory ware played a starring role in the creation of the first truly synthetic fiber—nylon—and in countless other chemical triumphs.

Glass in the laboratory helped to give us margarine, the popular butter substitute of which the United States alone uses 500,000,000 pounds a year. Glass serves in testing and transporting our dairy products and other foods, and in making, distributing and using acids, dyes and liquids of every imaginable kind.

Special glass in the control-booth windows in steel mills protects workers from the unbearable heat of white-hot metal. In steel mills too, special glass forms the traveling crane's cab windows to shield the operators from the heat of its loads of molten steel.

Glass serves in many ways in the electronics field, insulating, protecting, carrying and storing electric current. In ribbon form it is an important component of capacitors and condensers used in practically every piece of electronic equipment made.

Television could not exist without glass; nor, for that matter, could telegraph, telephone and power-line insulators, motion pictures, radio or radar.

Airport control towers are encased in glass. Airliners and other planes have windows of strong safety glass. Military aircraft use bullet-resistant glass for windows and gun turrets. Passenger cars and trucks use shatterproof safety glass. Airplane propeller blades are coated with glass-reinforced plastic, and some helicopters have whole bodies made of glass-reinforced plastics.

Glass nose cones strong enough to withstand the strain of faster-than-sound flight, equip defensive missiles of unbelievable accuracy. These nose cones help the missile to "see" and pursue infrared heat waves that streak from the exhausts of enemy jets and missiles.

Glass pipelines and tubes are used in laboratory testing of rocket fuels before they are tried in launching missiles, satellites, rockets and space capsules.

In orbit, our astronauts look out of heat-resistant panes of glass engineered to stand up under the blazing heat and the thermal shock that must be undergone during launching and reentry. Another specially constructed glass prevents loss of cabin pressure and also prevents water from coming into the capsule after splashdown. This glass is tempered to ensure greater strength. Antenna shields of space capsules are of glass. They protect both transmitting and receiving antennas from reentry shock and heat. Many parts of each manned spacecraft are made with fiber glass.

On ships at sea, the captain's bridge is enclosed in glass, and special glass is used in other windows and portholes. Specially designed lenses are used for running lights, for light buoys, lighthouse beacons, even seagoing lanterns. Portholes of warships and cruisers are glass; the periscopes of submarines depend on glass lenses and prisms. Glass protects the crew from radiation in atomic submarines.

Streamlined trains use specially made tough glass for windows, while some buses and railroad cars have all-glass vista domes. Railroads depend on glass signal lights for their safety, and fiber glass insulates steam boilers and heating equipment for railroad passenger cars.

Airport beacons, runway lights and field lights help pilots to safe landings. Laminated safety-glass windshields, many of them heat-conducting to prevent the formation of ice, perform a great service to aviation. Glass level switches assist in keeping airplanes on an even keel, and fiber-glass insulation keeps passengers and crews warm in the cold air of high-altitude flying.

In sports there are many uses for glass. Fiber glass reinforces plastics for the handles of golf clubs, and tennis and badminton rackets. The same type of material goes into water skis and vaulting poles, bows and arrows, fishing rods, reels and tackle boxes, rowboat and canoe oars, and diving boards. A sailboat of aluminum, plastic foam and fiber glass was featured at a recent New York boat show. Fiber glass also makes up the inner hull of an outboard runabout that is nineteen feet long.

Our food supply would not be nearly so plentiful, were it not for versatile glass. Acres of tomatoes and other vegetables are grown in greenhouses of glass. Cows, calves, poultry, pigs, goats and horses all respond with better health and better performance if they are housed in buildings with a view. Solar farm buildings are light, airy, bathed in sunlight; warm in winter, cool in summer. Glass plays varied and vital roles on land, sea, in the air and in the limitless areas of space beyond our world. It is only within the last century that we have begun to realize the very nearly unlimited possibilities of the material we call glass. With glass being studied around the clock, and new types with new potentialities constantly being discovered, we can be sure that, important as is its current role, glass will have an even more significant future.

And now let us follow some of the early adventures of this material that serves man so well.

# 2. Glass in Ancient Times

THE VERY FIRST GLASS FURNACE WAS A FLAMING volcano. Millions of years ago rock melted in the intense heat within its red-hot core and was forced to the earth's surface, where it flowed down the steep sides from the crater. This molten rock is called lava. When it erupted it was so fiery it killed every living thing in its path. If it contained silica (one form of which is quartz sand, a compound of silicon and oxygen) and cooled rapidly, it formed a shiny, hard, usually brownish material called obsidian—a true glass made by nature.

Back in the far distant past, cavemen now and then stumbled upon pieces of obsidian. They found that they could flake and chip it into weapons and tools. With sharp spearheads of obsidian they killed the huge prehistoric animals that were their major food supply. With knives made of obsidian they skinned and cut up their prey.

In later times obsidian was treasured for its use in ceremonial masks, mirrors, jewelry, containers, and even as a crude sort of currency. For thousands of years nature's glass was sought as men now seek precious minerals. Objects made from obsidian have been found all over the world. Both the Egyptians and Syrians made art objects of it.

In Yellowstone Park, Wyoming, there is a large mountain of this volcanically created glass. Most of the mountain is wooded and looks much like any other. But part of one side is bare enough to indicate that it merits its name: Obsidian Cliff.

Another kind of natural glass is found in the shape of a small stone. This type is produced only when lightning strikes a field of grain and fuses the silica and other minerals the grain contains. Lightning also produces another form of glass when it strikes a beach, fusing its silica, lime and soda into long, slim tubes of glass. These tubes are called *fulgurites* from *fulgur*, the Latin word for lightning.

Dark, usually bunshaped meteors, called *tektites* (*tektite* comes from *tektos,* the Greek word for melted) plummet down from outer space to land on earth. Found on every continent except Antarctica and South America, they are formed of glassy material much like obsidian. Some scientists think that tektites were tiny molten drops splashed into space by a giant meteorite that crashed on the moon. Another theory is that they were once melted scraps of the earth's crust that were thrust into orbit by meteorite impact and have now come back to earth. No one knows which belief is correct. But there are indications that tektites were shaped by the heat of friction as they entered our atmosphere—the same friction that burns up the heat shields of space capsules when they reenter our atmosphere after their journeys through space. Most tektites are found in Australia and parts of Southeast Asia. Some, however, have been discovered in the southern area of the United States. One was found on Martha's Vineyard, an island off the Massachusetts coast. Their shape, weight and color vary. But tektites, too, were used by the ancients as weapons.

The sea contains its own kind of natural glass. It consists of the skeletons of microscopic, one-celled organisms known as radiolaria—probably the world's oldest group of fossil animals. Radiolaria skeletons are formed by these minute sea creatures from silica present in sea water, resulting in extremely complicated, very beautiful, shell-like formations. These creatures are like much larger shellfish: they carry their houses on their backs. But completely *un*like shellfish, the material of these skeletons has the physical characteristics and the chemical composition of glass. Usually found near the surface in warm waters, the delicate skeletons finally sink and form deposits of siliceous material (composed of fine, flintlike sand) on the sea floor. This substance is known as Barbados earth. It is used by jewelers in grinding and polishing precious gems.

As we have learned, various kinds of nature's glass were discovered, put to use, and treasured by primitive man. We can imagine him showing off his finest specimens in somewhat the same way that a stamp or autograph collector might today. But although primitive people valued their obsidian and tektite-mounted spears, tools and ornaments, there is no indication that the idea of creating glass for themselves ever entered their heads.

The earliest known man-made material that is *like* glass was the faïence made by the Egyptians before 3000 B.C. Its interior, you will remember, was a white, porous material of crystalline quartz grains loosely bound together by a glasslike material. True glass, however, does not contain crystalline material, is not normally porous, and has no noticeable empty space between its component materials.

The outside surface of early Egyptian faïence *is* a transparent glass however. It is usually blue or green. Yet there does not seem be be any significant difference in the chemical composition of its exterior and interior. The production of the exterior glaze remains a mystery. Did the outer "skin" of faïence react to heat differently than the internal material? Or was a coating of the same basic material applied to the body of the piece, which produced the glassy surface when it was subjected to the firing process? The experts are still trying to determine this.

But the fascinating and perhaps far more difficult question still remains: since the basic materials of faïence and true glass differ only slightly in their proportions, why did it take a thousand years of making faïence before the Egyptians, or somebody else, made true glass? Higher temperatures, longer heating, or slight changes in proportions of the ingredients—any of which could have occurred by accident—might have produced true glass. Perhaps it did! But perhaps the faïence makers rejected true glass as something they didn't need or want.

Or perhaps the fact is that furnaces capable of reaching high enough temperatures had not yet been developed. But in other parts of the ancient world there seem to have been kilns that could supply enough heat. So once again we are faced with a mystery.

What we can be sure of is that as long ago as the Eighteenth Dynasty (1580-1350 B.C.), the making of glass was a thriving business in Egypt. This may have been at least in part because Egypt was abundantly supplied with everything necessary for making glass: silica, alkali and fuel. With a wealth of sand there could be no shortage of silica. Lakes of natron (native sodium carbonate) furnished the soda (an alkali) that was needed. Also, Egypt was more wooded in ancient times than it is now. So fuel was plentiful.

In studying ancient glassmaking one is sometimes puzzled that dates assigned to very early glass in older books and articles do not agree with those of more recent publications. For example, a book published in 1951 speaks of glass vessels having been manufactured as long ago as 5000 B.C. But today no positive date earlier than 1600 B.C. can be assigned to any vessel made entirely of glass.

The fact is that modern instruments of chemical and physical analysis are revealing so much about ancient glass that dates of manufacture, countries of origin, and other information can now be learned more accurately. Because of these new methods we are quite certain that all-glass vessels do not date back to such early times as was once believed. Far from taking away from the romance of glass, such highly scientific techniques for investigating early glass are adding exciting new chapters to the entire subject.

The latest studies of ancient glass are helping to rediscover lost trade routes. Much has been learned about the exchange of goods in early days. There are, for example, new indications that the Mediterranean region and Central Asia were linked by ship and caravan nearly 2,000 years ago.

Modern methods have also made possible an important new system for classifying ancient glass. This will go a long way toward establishing proper dates and other information about early glass, as new finds are uncovered.

Perhaps the thing that glass students most wish for is that some archaeologist will uncover the site of a really ancient glass factory. Meanwhile we can do little more than guess that early furnaces were crude and simple. They are thought to have been circular in form as a rule, with a hole or holes through which flames spurted. They may have included a section at the top for slowly cooling a formed piece of glass after the fire was out. Straw was used as fuel in some very old furnaces. But wood or charcoal usually provided the fuel until coal finally replaced them. England outlawed the use of wood in her glass furnaces in 1615 and converted to coal. But the worldwide use of coal was not common until the 1800's. Today it has been replaced largely by gas and oil, which are far simpler to handle and control.

In their old wood-burning furnaces, the glassworkers of Egypt used antimony, manganese and copper with sand, lime and soda to create glass that became opaque white, or purple, or green or blue when it solidified.

Sometimes it was carved into jewelry. Often combined with precious stones, it was highly valued and rare examples of this beautiful work have been unearthed in ancient tombs. A fine specimen is a collar of glass, gold, lapis lazuli and jasper found in the tomb of Tutankhamen. The Chinese and Mesopotamians (Mesopotamia is now Iraq) also imitated precious stones. Some workers were so skillful that bits of their blue and green glass are occasionally mistaken for gems even today.

Hollow glass vessels were made in all sizes and colors. One early method of creating them was to form them around a core of sand or clay. The core material was scraped out when the bottle or jar was finished. Old as some glass vessels are, they often contain bits of the material of which the core was made. The core material was first stuck to and around the end of a rod. Then the glass objects were built up by rolling or dipping the core at the end of the rod into glass softened by heating. The rod, of course, was used as a handle. Later, threads or canes of hot colored glass were applied as a decoration. The vessels—still hot—were then rolled on a flat surface of rock or charred wood until the threads became flush with the surface. They could be reheated and "combed" with a sharp-pointed tool to create an even more complicated design. When cooling had contracted it, the rod was withdrawn from the glass "shell" and as much as possible of the sandy core was scooped out.

When all these steps had been taken, there was a little glass jar or vase of exquisite beauty. These were among the first of the all-glass objects. They were of great value, for it took a lot of skill, work and time to create them. Only rulers and priests could own such rarities.

It was once thought that such objects were built up solely by winding hot, soft threads of glass around the clay or sand core. This idea is no longer accepted. Examination under a microscope shows no glass streamers or bubbles, which would surely be present had the winding method alone been used without first building a body by dipping or rolling the core in molten glass.

None of the very early glassmakers had any knowledge of glassblowing, the process that accounts for much of the hollow ware of later times. As you will see, it was much later that the Egyptians and others were to bring both blowing and molding to a high art.

Meanwhile those famous traders, the Phoenicians, carried Egypt's astonishing variety of glass creations to every port of the Mediterranean. It was soon found that one of the many unique characteristics of glass made it ideal as a container for oils, honey and wines. For, as we know, glass under usual circumstances is impervious to moisture and many corrosive influences. It therefore preserved merchandise far better than the casks of wood or jugs of clay that had been used for centuries before.

With its thriving glass industry, the country of the Nile grew more and more prosperous. But glass, although still a prized luxury, was losing some of its mystery appeal as the Phoenicians found an ever-widening market for it throughout their world of trade. Then, about 1200 B.C., Egypt's glass manufacturing started into a long decline.

From the first century B.C., the Roman Empire established glass factories. They imitated porphyry and onyx. The baths of Pompeii boasted the first glass windows—small, crude panes of cast glass set in bronze frames. Although they were half an inch thick, they let in some light, and they did help to keep out the cold. Following in the wake of the Roman Empire's military victories, the glass industry spread to almost every part of the known world.

Greece, too, had a few glass factories. Oddly, though, glass did not find outstanding favor in that country so celebrated for its high artistic attainments.

Probably a little after 50 B.C., some unknown glassworker finally invented the blowpipe. This was one of mankind's greatest discoveries and perhaps the most important event in all glassmaking history. Glass could no longer remain a luxury for the few. The blowpipe was to speed up production and make glass a necessity for the many.

It seems very strange that the blowpipe with its magic bubble was so long in appearing on the scene. Like glass itself, why was it not thought of far earlier? For centuries glassworkers had been pushing an iron rod tipped with an open knob into cauldrons of glass, picking up molten blobs at the end. It needed only a clever worker to replace the solid rod with a hollow, and perhaps a longer one. Surely then, someone would have puffed on the hollow rod, and the bubble that was to transform the glass industry, as well as much of the world, would have been born much sooner.

The giant stride had finally been taken; the blowpipe was a fact at last; but it didn't happen, probably, until some time after 50 B.C.

Once the blowpipe was in general use, glassmaking developed at an astonishing pace. In fact the glass industry grew faster in 50 years than it had in the previous 1,500!

# 3. The Blowpipe's Magic Bubble

THE ROMANS WERE THE FIRST TO GRASP THE potentialities of the blowpipe. They spearheaded and developed the expanding manufacture of glass into a large-scale industry. As the Roman Empire spread, glassmakers followed the conquering legions; glass manufacture prospered in many different places.

Sometime during the latter part of the first century before the birth of Christ, the Romans reached another milestone. Using fairly clear glass, they made the first relatively transparent sheets of glass for windows. Although their method is still debated, it seems to be agreed that the blowpipe made this possible. They also blew glass into clay molds to make plates, bottles, flasks and tumblers. A middle-class Roman family probably had crude glass windows, glass tableware and even cups inscribed with the names of popular gladiators. They also had simple glass funerary urns to hold the ashes of deceased relatives, while wealthy Romans treasured far handsomer urns, as if they were made of gold.

All this was made possible by the blowpipe, which had speeded up the manufacture of glass to what must have seemed a dizzying pace.

Early Roman Empire glass artisans also knew how to cover one color of glass with another and then cut away parts of the outer layer to leave a beautiful design against a background. This is called cameo glass. The outstanding example of this ancient work is the famed Portland Vase, now in the British Museum in London. This remarkable triumph of glassworking skill is now believed to have been made sometime late in the first century B.C. It is decorated in white against a deep blue undercoat—favorite colors for such pieces. Although the vase was broken to bits in 1845, it has been painstakingly restored and is today one of the world's most priceless art treasures.

When mosaics were first made, marble and stone were no doubt the original materials. But picture designs were created with bits of opaque glass, with stone and with ceramics when they became available. Created in all kinds of colors, they were called millefiori mosaics, and used by the rich as decorations on floors and walls. *Mille* is the Italian word for thousand and *fiori* means flowers.

For 300 years the glass industry prospered wherever Rome ruled. It was especially important in Syria, Italy, Egypt and the western provinces of Gaul—that sprawling country south and west of the Rhine, west of the Alps and north of the Pyrenees—a part of which is now France.

By this time there were so many glassmakers in the city of Rome itself that an area was set apart for them alone. In the year 200 A.D., eyeing the industry's prosperity, Emperor Severus imposed a high tax on it. Later in other parts of the world a heavy tax was imposed on windows.

The Roman Empire, as we know, did not maintain its supremacy forever. As its great power waned and the barbarian tribes of Germany plunged West European arts and sciences into the shadows of the Dark Ages, the glassmaking centers shifted eastward. The capital of the Roman Empire, Constantinople, named for Rome's first Christian emperor, Constantine, had been known as Byzantium. Today it is Istanbul, Turkey. There in the 500's Emperor Justinian had skilled workers make designs of mosaics for the city's great cathedral—the Hagia Sophia (Greek words for "Holy Wisdom").

During that same century, in another part of the world, we now know that a very large slab of glass was made. Almost 1,500 years later when it was finally discovered, it was not only a marvel but another one of the many mysteries of the world of glass.

This is the block of glass, approximately eleven by seven feet, found about 1956 at the ancient necropolis (burying ground) of the Beth She 'arim in Israel. Next to the 200-inch reflector on Mount Palomar in California, it is the largest piece of glass known to exist. The 18-inch thick piece of green-streaked, raspberry-colored opaque glass was found in the exact spot where it was made and still lies. When archeologists discovered it while clearing out an ancient cistern, it was not at once recognized as glass. It was left in place and a stone floor was built around it. A number of years later a three-inch core was drilled out of the slab and taken to the

Corning Museum, directed by Dr. Paul N. Perrot, in Corning, New York. In 1964, the laboratory tests proved that the big slab *is* glass and essentially similar to other glass made in the same area in ancient times. Scientists also demonstrated that the original batch of raw materials must have been melted by the unusual method of heating from above—probably at intense heat for several days. Glass experts are amazed that so large a slab could have been made in early times.

Why was such a slab cast? It may have been produced to make glass that could later be broken up and taken to small-scale glassmakers in various villages. Presumably they would have remelted it and made various articles of it. Or the entire slab may have been intended to serve some ceremonial or architectural purpose. It is believed possible that a thorough study of early Jewish writings may give us a clue to its intended use. Meanwhile the astonishing find is another unanswered riddle along the historic trail of glass.

In 1964 another startling discovery was made at Kenchreai, an ancient harbor at Corinth in Greece, this time by archeologists of the University of Chicago and Indiana University, headed by Dr. Robert L. Scranton of the University of Chicago. The group unearthed marble floors (below the present sea level), remains of buildings, a stairway, and astonishing amounts of such objects as wood, ivory and glass of a period perhaps not much later than 100 A.D. In the summer of 1965 an extensive marble mosaic floor was uncovered. Arranged on it in neat stacks were found some 100 "stained-glass windows" or glass mosaics mounted on plaster, some as large as four to six feet long and two to four feet high. The glass is opaque but thin, and it is cut into shapes of flowers, people, animals and towns.

The unique find is still too new for archeologists to give firm answers to such questions as: Is a pictured town Egyptian, Greek or Roman? When was the glass made? Where was it designed and constructed? For what use were the panels intended?

When the answers are finally given they will no doubt shed much light on many of the puzzles of ancient history.

Eventually glassworkers devised an ingenious way to make glass in small, flat sheets. They blew a bubble, set a solid rod into it at the opposite end from the blowpipe and broke the bubble away from the blowpipe. This left a roughly circular hole where the pipe had been. Holding onto the rod, they then spun the hot, soft bubble around and around. It flared and flattened into a disk as if by magic. The magic was actually centrifugal force. (Take a furled but not fastened umbrella and spin it. You will see somewhat the same thing happen as the umbrella flies open—also by means of centrifugal force.)

At the center of the flattened glass disk was the crown, rather like a rough scar, where the bubble had been torn from the rod, or *punty* as it is known to glassmakers.

Sheet glass made by this method was called crown glass. Amazing as it seems to us today, most of the window glass of the entire world was made in this way until the 1800's!

You can see examples of this type of glass in old New England houses. It is often called "bull's eye" glass. The windowpanes are small and square with the scarlike "eye" in the center where the punty was attached. Swirled and uneven as it is, such glass was used around front doorways to provide a little light in the dark hallways of Colonial days.

About the year 1000, picture windows of stained glass began to be made. The use of this glorious glass spread from the East until by the late Middle Ages every possible European cathedral was given this magnificent decoration. In marvelous pictures created out of small pieces of richly colored glass, the glowing windows told sacred history to an age when few could read. Outstanding early examples of stained glass are the cathedral windows at Augsburg, Germany, made in 1050, and those of the Chartres Cathedral in France, created 100 years later. Other notable twelfth-century windows can still be seen at York Cathedral and at Canterbury, both in England. The unforgettably beautiful glass of Sainte Chapelle in Paris belongs to the thirteenth century and a little later. But there are too many wonders to even begin a listing.

In the late 1100's and early 1200's, French and German glassworkers were able to make comparatively large panes of window glass by blowing a cylinder, then slitting and flattening it. However, this method did not replace crown or "bull's eye" glass.

Roger Bacon (1214?—1294) the English scholar-scientist wrote in 1266 of the first really practical magnifying glass. Two hundred years later, the printing press was invented, reading skills spread beyond the cloister, and eyeglasses became a necessity for many. The amazing story of optical glass will be told in a later chapter.

In the following centuries, Europe acquired its own glassmaking city in Venice, Queen of the Adriatic and Europe's gateway to the East. Venice, a world power in the late Middle Ages, may have gained more knowledge of glassblowing through her vast trade relations.

In the 1400's and 1500's the romantic city of canals, palaces and painters continued to be the center of world trade, one of the great seaports of Europe. She was famous for her fine glass and remained a glass manufacturing center for 400 years. Mainly to guard the city against fires, Venice moved her glass industry to the nearby island of Murano, a suburb of the city. This move took place in 1291. In Murano the glassworkers and their families were under the stern rule of the Venetian Republic's grim Council of Ten.

Carefully chosen armed guards patrolled what is said to have grown into an unbroken mile of glass factories, where thousands of workers toiled behind bars. Murano craftsmen led a life that reads like a cloak-and-dagger tale. Guarded though the glassworkers were, English and French spies found ways to tempt them to sell their secrets.

For a long time the foreign agents had little success. A glassmaker once did escape to the very gates of Paris. But one of the Council of Ten's henchmen overtook him there and stabbed him to death. However, this is now thought to have been because of a private feud between the two men.

Glassworkers who followed the rules were well rewarded. An elaborate guild system, somewhat like present-day unions, protected their trade. In 1376 they had been given the rank of burghers (freemen) of Venice by the Senate. Master workers were allowed to marry off their daughters to noblemen, and the children of these marriages were considered, according to some authorities, to be nobility.

At first the Venetians seem to have made only windows, bottles, other simple vessels and mirrors. But by the late 1400's Venetian glass was elaborately enameled in deep glowing shades of green or blue. It was often fantastically shaped. Glassblowers made goblets in the form of gondolas, ships, pyramids, tubs, belfries, whales, lions and other animals, to list only a few forms.

By the mid-1500's the marvelous island craftsmen had learned to make a glass that was clear and transparent—the first glass of its kind. They called it *cristallo*, a word that obviously suggests the highly valued rock crystal the new glass resembled. (Our finest glass is still called crystal.) The Venetian *cristallo* could be worked to remarkable thinness, yet it remained bright and relatively clear. It too was blown into elaborate goblets and other articles, often with stems that represented dragons or snakes.

The glassblower of Murano was more artist than artisan. With his blowpipe he blew glass as fine as the world has ever known. He also made a real contribution to science, for his fine *cristallo* finally came to the attention of men who understood the physics of the lens. They were in search of a material with which to put these principles to work. *Cristallo* could be curved to lens form without losing its clarity. The forerunner of optical glass, it played a role in the development of the microscope, telescope, an early form of the thermometer known as the thermoscope, and a kind of lens used in the *camera obscura*, a forerunner of our modern camera.

With their *cristallo* the Venetians created mirrors for which they became world renowned. They made them from small sheets of glass cut from disks that had been spun exactly as those used for window glass.

Venetian mirrors were rare and expensive. Rich women wore them as ornaments set in jeweled ivory cases hanging from their belts. Men of rank fastened their plumed hats with pins inset with them. The way in which such mirrors were foiled, or backed, was kept so secret that Venice maintained her monopoly on them for an entire century. To help guard the method, scrap glass was not permitted to leave the island of Murano.

Finally, however, despite all precautions, Venetian glassworkers were lured to other countries. Trade secrets almost identical with those of Murano were given away by glassmakers of Altare, another Italian glassmaking center near Genoa, whose workers were not placed under any restrictions. On the contrary, Altare believed in teachings skills wherever they were needed. The craftsmen of this generous-minded city taught their techniques to the artisans of England, France, the Netherlands and Spain.

England's Queen Elizabeth I was very much interested in her country's glass industry. As early as the year 1570, the great Jacopo Verzelini came to England and in 1575 obtained a monopoly on making Venetian glass specimens. He taught his skills to some of the Queen's subjects. Verzelini engraved drinking glasses with a diamond, a technique rare even among the glass artists of Venice.

Glass at that time had great appeal for the English. For them the new transparent substance had the quality of a rare jewel. Shops glittered with glass of all kinds and the windows of the great houses were enlarged until people complained that a certain hall was "more glass than wall." In a room at Hampton Court, not far from London, there is said to have been a musical instrument of fairytale delicacy and beauty that was entirely made of glass except for the strings.

In spite of her high attainments, Venice was losing ground as the world's foremost glass manufacturer.

With some exceptions glass was created almost entirely for beauty—not for utility as it had once been in Roman days. Few people had glazed windows. Window glass was still only for royalty and a few of the nobility. Lesser Europeans stretched linen over their window openings or used wooden shutters to try to make the weather bearable. (Incidentally, in ancient Rome thin slices of marble, horn and mica had been used over window apertures, and the Roman Emperor Hadrian, who lived from 76 to 138 A.D., had a window "glazed" with paper-thin alabaster in his magnificent villa near Rome.)

During the 1500's the rich and mighty who owned windowpanes preserved them with the greatest care. If they closed their imposing houses to go on a journey, it is said, the windowpanes were sometimes taken down and carefully packed away until the owners came home. In their wills the proud possessors of window glass bequeathed it to specially designated heirs.

With the spread of her once closely guarded glassmaking skills and the discovery of the new sea routes around Africa and to the New World, Venice lost her place of preëminence. Spanish, Portuguese, French, English and Dutch fleets took over world trade. Venetian glass designs and methods were now known to almost every country of Europe.

But Venetian glass artisans did not give up, by any means. Today they still make beautiful and rare glass on the very same island of Murano to which they moved in 1291. Now, though, they must share their fame with that of glassmakers elsewhere in the world.

The 1500's and 1600's had been a real turning point in glassmaking. Very early in the 1600's, many important tools of science first came into use. At that time, too, a remarkable book—*The Art of Glassmaking*—written by Antonio Neri, was published in Florence, Italy. It was the first of its kind ever written and included the history, chemistry and craft of glass manufacture. Published in 1612, it added tremendously to the knowledge of glassmaking all over Europe.

The age of modern glass had actually begun. As we have seen, with the perfecting of *cristallo* early in the 1500's, glass with its unique and varied qualities had begun to assist in creating laboratory equipment that made possible the majority of our great scientific discoveries.

Though he did not invent the telescope, Galileo improved it early in the 1600's. The year he died, Newton was born. Sir Isaac Newton and other science-minded men experimented with special kinds of glass. In 1666 Newton began research that led to the conclusion, in 1672, that white light is made up of many different colors; that with the use of a glass prism it can be broken down into the colors of which it is composed. He experimented with many different types of glass and in 1668 produced one of the earliest, if not *the* earliest, reflecting telescopes. A Dutch merchant, Antoni van Leeuwenhoek, made more than 250 simple microscopes. By using them he discovered the corpuscles in the blood and many other tiny organisms. His work, along with that of Robert Hooke opened the door to modern microscopy and to the growth of bacteriological exploration.

About a decade later the French learned to cast, grind and polish glass. Their method was to pour molten glass onto a bronze table as some believe the Romans may have long ago poured it onto sanded stone. This made the French supreme in the polished-glass field for many years. The casting process appears to have been the invention of Bernard Perrot, but it was developed by Louis Lucas de Nehou.

The French also discovered that the Venetians' mysterious method of making their beautiful mirrors was to back the fine mirror glass with a coat of mercury. The canny French combined the two processes—casting and foiling. Now for the first time in its long history, glass could be cast, ground, and polished, thereby emerging completely flat and almost clear of bubbles. It could also be made in very large sheets.

Louis XIV was entranced. He ordered mirrors for all his elegant coaches and, more important, for the great palace of Versailles outside Paris. There, his 240-foot-long Hall of Mirrors now attracts thousands of tourists year in and year out. These mirrors were blown in the old way. But those in the French king's other palaces were cast.

In King Louis' time, mirrors became the rage all over Europe.

We all know the superstition that to break a mirror is supposed to bring seven years of bad luck. Historians now tell us that this tale was invented as a warning to servants to "handle with care" or suffer dire consequences!

A novelty of the late 1600's were Prince Rupert drops, named for Prince Rupert, the Duke of Bavaria. The story is told that Rupert was invited to show one of these amazing bits of glass to King Charles II of England.

The Prince knelt and placed on the marble floor a tiny drop of glass that, with its thick "head" and tapering "tail," resembled a polliwog. He then struck the fragile-looking glass with a heavy hammer. It did not so much as crack! Then he mildly tapped the tail, and the glass polliwog flew into a thousand pieces!

The King was completely baffled. "It must be witchcraft," he said.

But Prince Rupert drops are made by merely letting a molten drop of red-hot glass fall into cold water so that it chills suddenly. In falling to the water the drops become pear-shaped with a slender tail. The glass is abnormally strong on the surface. But its sealed-in energy is so great that if the slender, faster-cooling tail, where there is much less tension, is even scratched, the entire drop explodes.

Such drops may at first have been made by accident and then used only as a trick. But the method later contributed to the development of glass-strengthening by heat, or tempering, as the process is known.

In a later chapter the making of Prince Rupert drops will be described in detail so that you can make these strange little polliwogs of glass that a king once thought were created by witchcraft.

Before King Charles was baffled by Prince Rupert drops, glass had come to be thought an indispensable material as well as a beautiful art medium. It was used all over Europe and in the East where it had been made for so long. But glass, which had for centuries traveled over so many miles of trade routes on land and sea, was destined to take still another long journey. At the end of that trip the magic substance with its many unmatched qualities was eventually to find its largest market. It would be manufactured in the greatest quantity and in the finest quality on earth. Its makers were to discover new and essential uses for it in every branch of industry, science and commerce. But not before the transplanted enterprise had surmounted many disasters and overcome many obstacles.

In 1608 glass began to be manufactured in Jamestown, Virginia, in the New World, to which Columbus had opened the door only about 100 years before.

# 4. Glassmaking: The New World's First Industry

IN 1607, WITH CAPTAIN JOHN SMITH AS THEIR leader, a valiant little group crossed the Atlantic to establish the first permanent colony in the New World at Jamestown, Virginia. A year later another ship sailed into port bearing seventy passengers. Among them were eight Polish, Dutch or German glassworkers who had been sent by England's London Company to organize a glassworks—the very first industrial enterprise in the New World.

Coal was not yet used in glass furnaces and this daring venture had come about because glassmaking was fast using up all the timberlands of England. The English had to have wood for their big navy, and only a few years later (1615) the Crown was to forbid the use of wood for glass furnaces.

Meanwhile the New World, it was said, had vast forests growing near its sandy beaches. Why not set up a glass industry where now was only wasteland? Surely it would be very profitable, as it had been in Venice. The London Company had splendid dreams of the future of the Jamestown glass factory. It would supply the world with glass dishes, tumblers and bottles.

Reality, though, proved to be far from the dream. A humble factory was built with one main furnace and three lesser ones. We can only guess at what it produced, for the factory opened in 1608, lasted only a year and left no clues. (If any of the crude glass made there could be found and authenticated, it would undoubtedly be worth a fortune!)

In Jamestown there were famine, trouble with the Indians and other hardships. The brave little colony, estimated at 500 settlers to begin with, wound up with less than 100. The glassworks closed. Twelve years later the London Company sent a band headed by Captain William Norton and six Venetian glassmakers to the same spot.

But disaster was in store for them, too. First a windstorm almost destroyed their factory. Then in 1622 Indians ruthlessly massacred many of the group. Once again glassmaking was abandoned.

There were other attempts to organize, but the first successful glassworks in this country was not founded until more than 100 years later—in 1739. This was the enterprise of Caspar Wistar, a forty-three-year-old brass-button maker, a native of Germany who had come to the colonies in 1717.

Wistar employed four glassworkers of either Dutch or German origin to work in his Salem County, New Jersey, factory and to teach him—and his son Richard—the art of glassmaking. In Wistarberg, as the area was later named, window glass and various kinds of bottles were turned out as the business prospered. Caspar Wistar died in 1752, leaving both his thriving button works and his glass factory under the supervision of his elder son, Richard. Richard sold bottles to traders who were smuggling molasses from the West Indies. But soon he expanded to make a dense, plain, transparent glass of high lead content (called flint glass) for tumblers, bowls and jars. The business lasted until the Revolution signaled its death knell.

The next important figure to appear on the American glass scene was also a German—Henry William Stiegel. A colorful person, he bestowed on himself the title of Baron of Manheim, Pennsylvania. Stiegel, though skillful, was so eccentric that he might be called an egomaniac. He chose Lancaster County as his base of operation, married the daughter of a successful iron-foundry owner and became a partner in the business. Before long he set up a glass furnace in the foundry and made bottles and windowpanes. Soon he built two factories of his own, imported artisans from England and Germany and began to operate on a very elaborate scale with money that he borrowed.

Stiegel built a castlelike mansion at Manheim and, fantastic lover of display that he was, had a cannon set on one of its towers. Whenever he returned home from work in his rococo gilt coach with trumpeters preceding him, the cannon would boom forth the proper salute!

This musical-comedy industrialist played his elegant role for only nine years. He came to a tragic end. About 1774, the "baron's" extravagances landed him in a debtors' prison. Some ten years later he died in abject poverty.

In the meantime, though, this strange man had come a long way from bottle and windowpane manufacture. Often copying elegant imported tableware, he decorated his glass with engraving (the process of cutting designs on glass by abrasive means), pattern molding and enameling, sometimes in true-to-the-period Pennsylvania Dutch designs in color. He created some of the loveliest art glass this country has ever seen. Pompous though he was, he was a meticulous producer.

During his brief heyday, Stiegel built a Lutheran church at Manheim. In 1772 he gave its trustees both church and the land on which it stood, asking only a token fee in return, as was the custom of those times. He asked for the "payment" of one red rose each June. To this day on a certain June Sunday, a single red rose is placed in the "baron's" church in memory of an odd but very great glassmaker who left a wonderful treasure of fine glass to his adopted land.

John Frederick Amelung, born in Bremen, Germany, is called the most gifted glassmaker of his time in this country. He established a glassmaking colony in New Bremen, near Frederick, Maryland, about 1787. There he made fine quality glass for a relatively short period. Although Amelung had come to America with considerable capital and about 300 workers, including blacksmiths, bakers, shoemakers, teachers and a physician, a variety of misfortunes finally forced the talented German to ask the government for a loan. It was refused and matters went from bad to worse.

Meanwhile, many distinguished men of the era were interested in our country's growing glass industry. George Washington is said to have written of Amelung's glassworking community in a letter to Thomas Jefferson. It has also been recorded that Amelung journeyed to Mount Vernon to deliver personally a present of handsome glass goblets to Washington.

After the eventual collapse of the New Bremen glassworks, John Amelung and his family moved to Baltimore, where he died on November 20, 1798. A son tried to revive his father's glass industry but had no better success than the senior Amelung. Nevertheless John Frederick Amelung left us a small but important heritage of glass treasures in the form of goblets and bottles, engraved in the splendid German tradition.

In 1825 a new name in early American glass came into prominence: that of Deming Jarves, founder of the Boston and Sandwich Glass Company in the town of Sandwich, Cape Cod, Massachusetts. This was among the first American glassworks to be operated on a large scale with workers trained in the United States. It was a fast-growing concern and was soon melting 100,000 pounds of glass a week. It is said that in 1827 a company carpenter, Enoch Robinson, who had a talent for invention, devised a way for pressing glass into molds of iron. The company did use this process, although there is some doubt that it originated in this way. At any rate, the method made the company over from a manufacturer of high-priced art objects to one that made attractive pressed ware now called Sandwich glass. The price was within reach of almost everyone.

Small cup plates were among the pressed-glass articles made by the Boston and Sandwich Glass Company that are collectors' items today. These little lacy patterned plates are about three inches in diameter. They were fashionable at tea time in the 1800's. In those days cups were made without any handles, and their saucers were in the shape of shallow bowls. The custom was to pour the hot tea from one's cup into the saucer, set the cup on the tiny glass cup plate and drink from the bowl-like saucer!

In early times master glassblowers got no more than $14 a *week* while toolmakers and others received $6 and boys—in those days of child labor—$3. The Boston and Sandwich Glass Company, however, was so successful that Jarves raised his workers' wages to the amazing sums of $4 and $6 a *day*.

In 1859 petroleum was discovered, and with the invention of the kerosene lamp there was a huge market for lamp chimneys. "An oil lamp for every room" was the slogan of the moment.

Except for fires for cooking and heating, the candle and smoky liquid tallow had been for many centuries the sole sources of light after the sun went down. It wasn't until 1784 that anyone made a major improvement in oil lamps. The new lamp was the work of a Swiss inventor named Aimé Argand. His invention seems simple, but what a difference it made! He found a way to carry air up through the center of a round wick as well as around the outside. For the first time in history, glass enclosed the wick's flame; the chimney was not just a smoke flue but a protection against the wind and a source of a steady supply of air. This was the first efficient artificial light. Then when petroleum was discovered, the glass lamp chimney was in real demand.

Along with several other companies, Boston and Sandwich profited. Tableware, too, was wanted in large quantities, with Jarves' organization alone making 100 tumblers an hour!

In 1888, though, the crisis came. Just after the company received a very large order for lamp chimneys, the workers threatened to strike for higher wages.

"If you don't meet our union's conditions," said the men, "we will walk out."

"Do it," dared the Boston and Sandwich Glass Company, "and we will never open our doors again."

The workers did not believe the threat. They defied the management and the bosses kept their word. This marked the end of the manufacture of Sandwich glass, pieces of which are rare enough today to bring high prices.

Until the closing years of the nineteenth century, American glassmakers did little to improve methods of making glass. They did what the Europeans had done, and not much more. Plate-glass and optical-glass manufacture were tried by many small glass factories in the United States, but most of them failed. They were merely duplicating what Europe could do more cheaply and far better.

By the end of the century, though, America had made enough scientific advances to industrialize its glassmaking on a firm basis.

From almost the beginning of the twentieth century until today, man has in a short space of time done an amazing job with glass.

Ever since the Egyptians learned how to make bottles, glass has proved a most desirable material for many kinds of containers. After the invention of the blowpipe, bottles could be made much faster either by blowing alone or blowing into molds. These methods were used until the 1900's. By that time partially automatic bottle-making machines were in use. But even with this improvement, such containers were still quite costly.

Then in 1903 a big step was taken in the glass industry. Michael J. Owens, a young, aggressive master glassblower from West Virginia, developed the first completely automatic machine for making bottles. The new method made mass production possible and cut the price of bottles until they were cheap enough for general use. In fifteen years Owens' bottle machine did more to revolutionize the glass industry than anything else had done for centuries.

Now and then you read of someone putting a message in a bottle and then dropping it into a sea or river. When the bottle turns up hundreds of miles away it becomes a news item. One of the oldest uses of the bottle is to study sea currents. It is said that this method was used about 300 B.C., when the Greek naturalist Theophrastus used floating bottles to prove that the Mediterranean gets most of its water from the Atlantic. Our own Benjamin Franklin learned secrets of the Gulf Stream by using bottles. Today ocean currents are still studied in this way.

Not long after Owens invented his bottle machine, Dr. Hervey Dexter Thatcher thought of using bottles for home-delivered milk. At that time milk was taken from house to house in big, loosely covered cans that were loaded into horse-drawn wagons. Flies, street dirt and dust made this system very unsanitary. Thatcher's tightly closed glass bottles were a big improvement and a real advance in disease prevention. This new use gave bottle-making even more impetus and glassmaking went full speed ahead. Today in this country alone bottles are produced in the billions each year. And now, except for art glass, nearly all glass is made by machines and by methods not even dreamed of before 1900.

Edward Drummond Libbey is another big name in the story of glass. In the late 1800's he made cut glass that was popular for a time. (It is currently enjoying a revival.) Owens became a valued executive in Libbey's factory at Toledo, Ohio.

Another great Toledo glass manufacturer was Edward Ford, son of Captain J. B. Ford, who pioneered plate-glass making in America. Mr. Ford built the largest plate-glass plant under one roof in this country. All three men died between 1920 and 1925, and in 1930 their companies merged into the huge and important Libbey-Owens-Ford Glass Company.

The Corning Glass Works, in Corning, New York, is known all over the world as the company that cast the 200-inch, 20-ton glass disk for the telescope at Hale Observatory, on Mount Palomar, California. Originally the Union Glass Company of Somerville, Massachusetts, this industry was founded by Amory Houghton in 1851. With some of the same family helping to guide its destiny, it moved to its present location in 1868. There in 1875 it was organized under its present name. To celebrate its hundredth anniversary, the Corning Glass Works opened the Corning Glass Center. There one may see glass products being blown and decorated, watch films on glassmaking history, and visit the famous Corning Museum of Glass with its marvelous collection drawn from far places and ancient times.

Still another great American glass producer, Pittsburgh Plate Glass Company, began its operations in 1883. Like Corning, it has far-reaching research and development programs. It employs some 33,200 men and women.

From its small beginnings in Virginia in 1608, the United States glassmaking industry has grown into a towering glass giant. Our country has made, and is making, immeasurable contributions to the world in new methods and new types of glass. Many of these will be discussed in later chapters.

Today we in the United States are the largest users and producers of glass on earth. The small industry that was our very first and that some three centuries ago seemed doomed to failure, has exceeded the London Company's wildest dreams. For we now manufacture more than 8,000,000 tons of glass each year!

# 5. About the Chemistry of Glass

When you meet a newcomer to your group or town, you note how he looks, his name and where he came from. Usually this happens quickly. But it takes a lot longer to find out about his likes and dislikes and how he behaves when playing games or in other situations. In other words, getting to know a person's character is much more difficult than forming a first impression of him.

So it is with a material like glass. We know what different types of glass look like, what they are called, and where they came from. Now, just as with our new human acquaintance, we are ready to take the harder step: we will learn something of the character of glass. Or, to put it differently, we will find out something about what it is like *inside*.

To do this, we need the help of a chemist. We will find him in a laboratory, wearing a white coat and perhaps studying the contents of a straight-sided test tube. What does he find so absorbing about all this and about arranging his laboratory glassware, rubber tubes and his carefully measured quantities of strange powders and liquids?

Well, the chemist is interested in the water we drink, the air we breathe, the paint on our houses, the natural or man-made fibers of our clothes, the ink on the page you are reading.

He wants to know why iron rusts in our automobiles as it comes in contact with air, with dirt, water and salt from the road. He wants to know why copper changes from copper color to green; why the film in your camera becomes black, after development, in the places where the whitest light struck the film after passing through your lens. Why does silver tarnish, why does brass corrode, why does gold do neither? Why does one dye in a piece of cotton or yarn of rayon, silk, wool or nylon stay bright and true, while another dye fades? Why does wood or gasoline burn, but not asbestos?

All these things and thousands more—about any solid, liquid or gas—interest the chemist.

Thousands of *things,* yet the chemist's raw materials are just the ninety-two elements in "Mother Nature's pantry" and a few more that have been made by man. The combinations of these elements account for the thousands upon thousands of things in our world, including you and me and the safety belts in your car!

What is an element? It is a single, pure substance made up of just one kind of matter. Neither you nor anyone else can break it down into anything else by grinding, hammering, heating, freezing or any other means short of blasting in an atom smasher.

Platinum, gold, silver, sulphur, carbon, calcium and cecium, and most of the other elements are solid. Two of them are liquid at room temperature: mercury which you know from thermometers, and bromine, which you are not likely to see outside a chemical laboratory or a factory. All the rest of them are gases: the nitrogen, oxygen and rare gases of the air we breathe; the chlorine you may smell in bleach or swimming-pool disinfectant; the neon of colored lights; hydrogen, argon, fluorine and many others.

But solid, liquid or gas, each of these is an element—a single, pure substance that you cannot make any simpler by any chemical or physical means short of that atom smasher. An element is one pure thing, not a combination of things.

But a compound? Here we get into combinations. For a compound is the result of two or more chemical elements that have been chemically joined together. The characteristics of a compound are always different from the individual characteristics of the two (or more) elements from which it was made. Burn hydrogen and oxygen together (they'll explode if you don't handle these two gases properly), collect the resulting compound in the right kind of chemical laboratory apparatus, and you'll find that you have an old familiar friend, $H_2O$. The $H_2$ stands for the hydrogen gas and the O is the chemist's shorthand for oxygen. And no doubt you already know that the compound is water. You will note that from two gases, once joined together in compound, you now have a liquid. And this compound, as you have just read, has characteristics which are different from those of the elements of which it is composed. From these potentially explosive elements, hydrogen and oxygen, you now have one of the mildest, most widespread compounds in the world. (*Chemically* mild, of course; we all know, to our sorrow, what happens when floods occur on land or hurricanes whip the oceans into mad, destructive waves. This is physical effect. But pure water is still chemically mild.)

Another compound you use every day is the table salt added to your food either in the kitchen, at the table, or both. The chemist knows it as sodium chloride, and as you may guess, it, too, is composed of two elements: sodium and chlorine. The chemical symbol that describes it is $Na\ Cl$.

Sodium ($Na$) is a solid. It is so active, so eager to combine with other elements, that if you touch it with wet hands, it will burn you. When you see it submerged in kerosene in the chemical laboratory to keep it away from air and water vapor, it looks innocent as can be. It is a soft metal with a dull, silverlike color and is fairly light in weight. But if you pick up a little piece with forceps and drop it into a beaker of water, hold a glass shield between you and the beaker or jump back! For *it* will jump, spitting fire and sputtering with every contact with the water.

Chlorine is the second element in our table salt, and it cannot be classified as a peaceful, mild citizen of the chemical world, either. It is a yellow-green gas, a corrosive gas that is eager to combine with nearly any one of the other ninety-one elements it may meet. This means that your lungs are susceptible, too. If you should whiff it slightly, it would choke you. If you were so unfortunate as to breathe too much of it, it could kill you. Yet when these two terrifically active elements combine, we come up with the mild stuff that you must eat in small quantities, or die: common table salt.

Every substance in the world is made up of elements. Pure copper, pure silver, pure gold? Each of these is a single element. Water is a compound of two elements in definite proportions. So, too, is common salt.

There is a third kind of substance in the world which accounts for most of the earth's bulk. This is a mixture. When two elements are physically mixed together—gold and platinum powder, let us say—or when two or more inactive compounds are mixed together without causing any chemical reaction, the result is a mixture. A mud pie is a mixture. Sand and water in a bucket is a mixture.

Milk is a mixture. Like all mixtures, each of the substances within milk can be separated by *physical* means. Let the cream rise to the top and it can be skimmed off—approximately 4 percent. By physical means you can separate the water, too: about 87 percent; casein, 3.3 percent; milk sugar about 5 percent and smaller amounts of mineral compounds and vitamins.

Petroleum, too, is a mixture. It is a mixture of gases, liquids and solids. Heat it under proper controls, and, again by physical means only, one substance after another boils off and can be captured and separated from each of the others. Some gases come off the black crude oil as soon as it gets slightly warm. One after another, the less volatile gases are driven off the mixture as the temperature rises. Later, with even higher temperatures, the liquids are vaporized, one after another, condensed, captured and stored in separate containers.

Some 450 years B.C. a group of philosophers held that if you were to take a piece of gold or silver, or any other element, you could cut it into finer and finer pieces forever. Like numbers, they said, no matter how small, you can always divide by two once more and once more, forever, and there is no such thing as an ultimately "smallest" piece of matter.

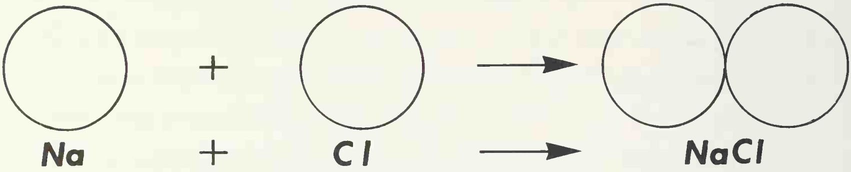
But the Greek philosopher Democritus, who died in 370 B.C., was the leader of another group who said that all matter was made up of indivisible small pieces that they called "atoms," a word meaning "cannot be cut." This theory has been accepted ever since, although nobody ever has had absolute proof that it is true. But as a working theory, it is enough to say that the atom is the smallest particle of an element that can enter into a chemical action.

Look at the illustration on page 60. It shows what happens when two kinds of atoms enter into a chemical action. When an atom of sodium and an atom of chlorine combine, they form sodium chloride, or common table salt, which is a compound.

Remember there are three classes of matter: elements, compounds and mixtures. The smallest particle of an element is an atom; the smallest particle of a compound is called a molecule.

The way in which atoms join with each other to form a molecule is constant and predictable. Only a single atom of sodium will combine with a single atom of chlorine to form a molecule of sodium chloride: NaCl—which is the chemist's shorthand for salt.

Here is an illustration:



Two atoms of hydrogen join with one atom of oxygen to make one molecule of water. This is the meaning of the little "2" below the line in the formula: $H_2O$. (Incidentally, the figure below the line is called a *subscript.)*

In the ammonia used in household cleaning agents, three atoms of hydrogen join with one atom of nitrogen: $NH_3$. Why?

It was discovered that the atoms would join with each other in specific numbers. Sir Edward Frankland named this characteristic in the middle of the last century. He called it *valence,* and explained it by saying that each element had its own characteristic holding power. In fact the word valence comes from the Latin *valere,* which means "to be strong" or "to have power." Hydrogen, said Frankland, in effect, has only one "hand" or hook; oxygen has two; nitrogen has three. So the two hands of oxygen can hold two of the one-handed atoms of hydrogen, and so on.

The forces that hold the different atoms together in the form of a compound are electrical.

Now you can see how this all applies to glass.

The chemical compound that is the principal constituent of most commercial glass is known as silica, the quartz sand that is the prized main ingredient. Silica is an oxide of the element silicon, which means that silicon is combined with oxygen. It has the chemical formula of $SiO_2$ and is usually present in commercial glass to the extent of 60 to 80 percent. Such sand usually comes from banks of sand such as those found in New Jersey or from sandstone that is found in several other states—Pennsylvania, West Virginia, Illinois and Missouri being important sources.

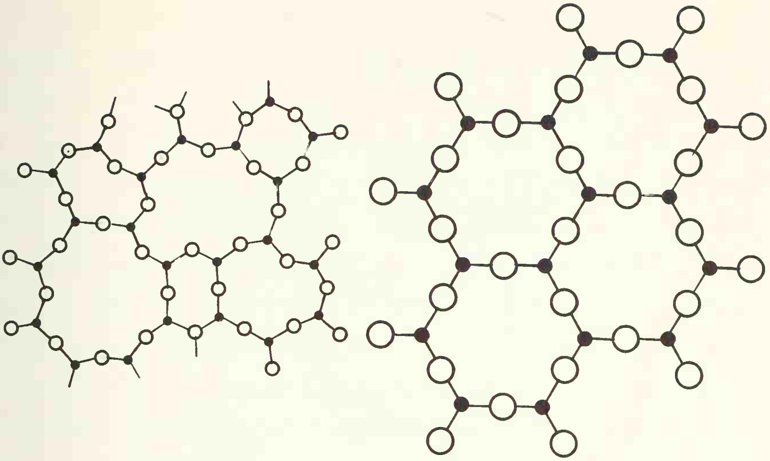
All sand has some ferric (iron) oxide ($Fe_2O_3$) in it, and since this is a very strong yellow or green coloring agent, glass manufacturers must be extremely particular about the composition of the sand they use. If they are making green bottles, they do not need to bother much. But if they are making clear, colorless optical glass for fine microscopes, telescopes or other instruments, they must be very careful indeed.

It would be very convenient if glass makers could mix sand ($SiO_2$) and soda (sodium oxide: $Na_2O$) and lime (calcium oxide: $CaO$), heat it, and know precisely what chemical reactions would take place and what they would get when their molten mixture cooled. But making glass is not so simple and definite as burning hydrogen and oxygen together and getting water. Far from it.

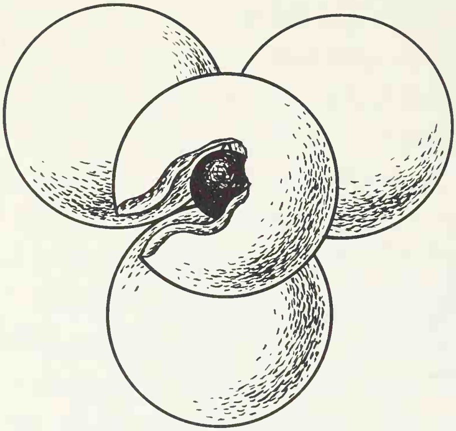
The composition and the molecular forms of glass are complex. No single chemical formula can be assigned to glass, for unlike table salt ($NaCl$) or water ($H_2O$), glass is not a single, chemical compound, but really belongs to the third category of substances: it is a mixture. (It has been called a "solid solution" or a "supercooled liquid" as a short route to describing its chemical and physical status.) But glass is not so simple a mixture as sand and water, by any means. For very complicated chemical changes *do* take place when the various raw materials of glass are melted together in the glass furnace. The result of these chemical changes is not a single kind of chemical compound. It is an intimate mixture of several different compounds. The description of the composition of a particular kind of glass can be given only by stating the proportions of the compounds included in the mixture. Glass manufacturers have a regular short-cut method of expressing this. They simply state the relative number of formula weights of the main ingredients used in making a specific glass. A statement like this is not a chemical formula. But to experienced glassmakers, the proportions of raw materials used in the original mixture identify the final product. One such statement would be this: $Na_2O : .67CaO : 4.52SiO_2$. It means 1 part soda, .67 part lime ($CaO$) and 4.52 parts of silica or sand.

Silica is the common name for the compound, $SiO_2$ which is composed of one atom of the element silicon and two atoms of oxygen.

A great deal of our knowledge of the composition of glass is the result of studies made with the X-ray. Look at the diagrams here and you will see the difference between the structure of a crystal of silica and that of silica glass. The absolute regularity of pattern in *any* crystal is characteristic, whether it is a piece of lead, sugar, copper



or salt. Each has its own particular kind of pattern. The two-dimensional crystal pattern on the left, in which the black circle represents silicon and the white circles represent oxygen, show a completely regular pattern, both in the molecule itself and in the relative position of each molecule to its neighbors. But in glass, while the position of each of the atoms in the molecule of silica is completely regular, the positions of each molecule relative to its neighbors is practically hit-or-miss. (These diagrams are two-dimensional representations of the true form of the $SiO_4$ molecule, which is actually one atom of silicon surrounded by four atoms of oxygen. To picture it approximately, think of four large glass marbles as the oxygen atoms: on the bottom will be three of the marbles in a triangle; on top of these three, place the fourth; just under the fourth, place a small black marble representing the



silicon atom that will just fit the space. Obviously a perspective drawing trying to show the three dimensions of such structures would become so complicated as to be almost meaningless.)

W. H. Zachariasen in 1932 established much of the thinking about the structure of glass. The fact that there is so much irregularity in the structure of glass led him to predict that there would be holes in the structure large enough to hold the various kind of materials that glassmakers use to make glass more workable and to lower its softening temperature. This proved true. These materials include the oxides of calcium, sodium, potassium, magnesium and lead. The oxygen atoms introduced into the glass mixture by the oxides break the strong network of the silicon-oxygen bonds and bring about the lowering of the softening temperature.

The number of possible glass formulas is infinite. Corning Glass Works has made up and tested many thousands, and the company develops new formulas every day.

The principal ingredient in the more than 8,000,000 tons of glass produced in the United States each year is silica in the form of sand. A pure silica glass can be and *is* made for experimental purposes. But it is not practical for general use. It requires extremely high temperatures to make it. When it is melted, it is such a heavy, thick material that it is almost impossible to rid it of trapped bubbles. Raising the temperature high enough to thin out the mixture vaporizes the silica completely. But if, instead of making a pure silica glass, the makers add sodium and calcium oxides, as noted above, the whole character of the glass is changed to a completely workable mixture.

The addition of small amounts of other chemicals brings about other changes. Borax and barium oxide help to melt sand more readily. Aluminum oxide helps to prevent crystallization of the glass as it cools. Sodium sulphate and arsenic oxide help in removing bubbles of gas and air from molten glass. Lead oxide is used in the highly important mixtures for optical glass and for the very finest tableware and art glass. Lead glass has greater brilliance than any other. Experimental glass has been made with a content of lead oxide as high as 92 percent, which makes it as heavy as cast iron!

Quite different from this is the kind of glass used in laboratory ware. "Pyrex," developed about 1912, is the special product of boric oxide added to the mixture of ingredients, plus a high content of silica. It is classified as a borosilicate glass. One formula for this type is:

| | | |
|---|---|---|
| $SiO_2$ | 80.5% | Silicon dioxide (sand) |
| $B_2O_3$ | 12.9 | Boric oxide |
| $Na_2O$ | 3.8 | Sodium oxide |
| $K_2O$ | 0.4 | Potassium oxide |
| $Al_2O_3$ | 2.2 | Aluminum oxide |

When you see *colored* glass, you may at first associate the process of making it with what you know about paints or crayons: red plus blue gives you purple, and so on. But color in glass is not made this way.

In glass, color is produced by a variety of means. Substances in solution in the glass can absorb particular kinds of light to produce a colored glass, yet the substance added to the mixture for that purpose may be a pure white salt! And, depending on the formula of the uncolored glass, the same coloring agent may produce any one of several colors. Nickel oxide ($NiO$) is an interesting example. One part of $NiO$ per 1,000 parts of glass will produce a noticeable color. But the colors will vary widely according to the original composition of the glass. It will be a reddish violet in a potash-lime glass ($SiO_2 + K_2O + CaO$), which is a combination of silica, potassium oxide (potash) and calcium oxide (lime); a brown-violet in soda-lime glass ($Na_2O + CaO + SiO_2$), which is a combination of sodium oxide (soda), calcium oxide, and silica; brown in a borosilicate glass like Pyrex, one formula for which is given above; and red in a lead glass such as the "crystal" glass used so much in fine art glass and fine tableware.

Here is a list of some of the colors that can be produced with the various silicate solutions indicated.

| | |
|---|---|
| Violet | nickel or manganese silicates. |
| Blue | cobalt silicates. |
| Greenish-blue | cupric (copper) silicates. |
| Green | chromium or ferrous (iron) silicates. |
| Yellow | ferric (iron) or cerium silicates. |
| Yellow | uranium compounds produce a yellow with greenish fluorescence. |
| Amber | iron and manganese silicates used together. |
| Gray, or smoked | manganese, iron and copper silicates used together in certain proportions, or copper and nickel silicates used together. |
| Black | high manganese content, the same manganese that is used to decolorize glass, if used in sufficient quantity will make a glass that looks as though it is black. A thin section shows that it is actually dark purple, but thick sections appear to be black. The same thing can be done with manganese, cobalt and copper or ferric silicates in combination, or with chromium and ferric silicates. |

There are various techniques required to achieve some of the colors, complicated methods such as melting the glass in a particular kind of gas and then reheating the glass until suddenly the color "strikes"—which means that it shows up brilliantly after apparently being a completely ordinary color, or almost colorless.

A good example of this is the fine ruby-red glass made by the addition of gold to the original mixture. One part gold in 50,000 can be added to the "batch," as the mixture of materials is called. When this is melted and cooled, nothing seems to have happened: the glass is either colorless or at best a light straw color. But when it is correctly reheated, its intense, beautiful ruby-red suddenly appears. Selenium used with cadmium sulphide and zinc oxide also produces good ruby-reds without costing so much as gold.

Perhaps this chapter has given you some idea of how much our scientists must know about the chemistry of glass. It is a vast amount. Yet they do not rest in their intensive effort to add more and more to their knowledge.

Perhaps, with their constant research, they may even be able to build glass bridges in shining, beautiful and permanent colors before the end of the century. Who knows?

# 6. Some Physical Properties of Glass

NOBODY HAS EVER ARRIVED AT A SIMPLE definition of glass on which all experts agree. Not all glass is transparent; some is not even translucent; not all glass is brittle; not all is colorless, or smooth. And the number of combinations of materials that can be used to make glass is so great that to generalize about them is sure to lead to inaccuracy.

To illustrate: opaque glass is frequently used on storefronts, on corridor walls in business buildings, in bathrooms in place of tile; and it is made in many colors. Fiber glass is not brittle in the usual sense, for you can bend thin pieces before they break; textured, figured glass is not smooth.

As for dictionary definitions, Webster's refers to glass as "an amorphous substance, . . . consisting ordinarily of a mixture of silicates . . . potash or soda, and some other base, as lime or lead oxide." Well, amorphous usually means without shape, formless, uncrystallized or unganized. These terms can give a wrong impression. And while the "mixture of silicates" is a usual one, the American Optical Company has made a glass that does not use silicates at all.

Many of the solid materials familiar to us, such as ice and metals (and some laboratory chemicals as well), change abruptly from solid to liquid when they are heated. When ice melts in a container, both the solid ice and the liquid water stay at exactly the same temperature until all of the solid becomes liquid. The reverse, too, is true: the temperature of the ice does not go down until *all* the water has changed from liquid to solid.

There is a pause "for station identification" as heating or cooling changes the condition from one state to the other. The same kind of thing occurs when solid copper changes to molten copper, when solid iron changes to molten iron or the reverse—each at its own specific melting and "freezing" point, of course. (Copper m.p.: 1083° C.; Iron m.p.: 1535° C.) Scientists usually refer only to "melting points" of materials that are solid at room temperatures, but the "freezing" point is the same temperature, just as ice at 32°F. becomes water at 32°F., and the reverse.

In the process of cooling and "freezing" or solidifying, metals, like water, form solids that have regular form, each one peculiar to itself alone, each with its own particular geometric pattern that is always the same for that particular substance. These are substances that have regular crystalline formations.

Glass is quite different from crystalline substances.

At room temperature glass is, in the usual sense, a hard, rigid substance and it stays that way when it is heated to several hundred degrees Centigrade. Then as the temperature is gradually increased, glass gradually softens and finally becomes a viscous (sticky and heavy) liquid without showing any quick change from solid to liquid at all. (One way of measuring viscosity is by timing a steel ball as it falls through a given distance in a liquid: the longer it takes, the more viscous is the substance.)

As the temperature goes up, glass of all kinds becomes liquid and takes on the characteristics of liquids. It takes on the shape of its container as water or soup takes on the shape of its pan; it flows under pressure as gravy moves when stirred with a spoon.

When molten glass cools it does not crystallize as metals do. In fact it becomes progressively more and more viscous in a regular manner until at room temperature it is finally the hard, rigid glass that we all know.

One authority, G. W. Morey, refers to glass at room temperature as having all the characteristics of a liquid except that it has become so viscous that it is rigid. Here is Morey's definition: "Glass is an inorganic substance in a condition which is continuous with, and analogous to, the liquid state of that substance, but which, as a result of having been cooled from a fused condition, has attained so high a degree of viscosity as to be for all practical purposes rigid."

All experts agree that glass, whether natural like obsidian, or man-made, is the result of heat and fusion. The natural glass of the five-by-nine-mile glass mountain in Yellowstone Park was the result of volcanic fusion.

In the Mediterranean, just north of the eastern end of Sicily, the island of Lipari is the location of two mountains of pure white glass that is again the result of volcanic action. This glass is white because it trapped billions of gas bubbles as it slowly cooled and solidified. This was nature's way of manufacturing that very useful abrasive: pumice. For that is the substance from which these mountains are formed. As you can see, man could never have made glass before he learned to build fires, or at least to keep them going once nature had started them with volcanic heat, lightning or spontaneous combustion. Making glass is an art that, so far, depends on fire. (That "so far" will be explained later, for there is just the hint of another means of creating glass, as you will see.)

The materials for glass were available long before man was on earth. Natural glass proves this, for most of it was produced many thousands of years before man existed. It is said that no other manufactured product is made from such inexpensive, plentiful and readily available materials. There will be more about this later.

It you have ever dropped a piece of glass on a hard floor and had it break or if you have ever thrown a baseball and had it go through a window, you probably think of glass as brittle and very easily broken. But "it ain't necessarily so." Let us take a look at some other characteristics of glass.

First of all there is its mechanical strength. C. J. Phillips wrote of this strength back in 1941, saying that it was "a complicated, perplexing, thoroughly misunderstood, and yet altogether fascinating property important alike to manufacturer and user." It still is, by the way.

All of us know that a spider web won't lift a steel beam into position on a new bridge. It takes a steel cable to do the job. We know too, that engineers can measure quite accurately the weight that the cable will lift. But the question of the strength of glass is far more complicated because it is highly dependent on characteristics of elasticity, hardness and brittleness—infinitely more so than are metals. We can see why this is so if we first look at the process of measuring tensile strength (resistance to longitudinal stress) of a piece of metal, and then see why the same method does not give the whole answer for glass.

To find the tensile strength of a piece of metal, a sample is pulled until it breaks. This is known as "testing to destruction." A sample of the metal under examination is cut to about six inches in length, put on a lathe and a section is turned very accurately to a diameter of .564 inch. That is the diameter of a circle with an area equal to that of a square that is one quarter inch on each side. (You'll soon see why this is a convenient size.)

Then a two-inch length of this turned section is very accurately marked off so that stretching can be easily seen when the tension is applied. The test piece is secured in a testing machine that is designed to apply a steady, measured, increasing pull on the metal.

Now, as the test starts, the pull increases gradually. If our sample is a piece of ordinary mild steel, the marks on our two-inch marked section will look exactly the same at the 6,000-pound pull as at the beginning, as far as we can detect with the naked eye. But under the microscope it can be seen that the metal has stretched, let us say, from 2 inches to 2.01 inches. Release the tension and the microscope will show that the marked section has returned to exactly 2 inches. To that extent the metal is elastic.

But if we apply the tension again until the pull is 8,000 pounds, then release the tension and measure again, we find that the metal has been permanently deformed. It has been stretched beyond its "elastic limit." Now you see why that .564 diameter is a convenient size for testing: since the section is one quarter of one square inch, multiplying 8,000 pounds by 4 tells us that the point at which this metal reached its elastic limit was below 32,000 pounds per square inch.

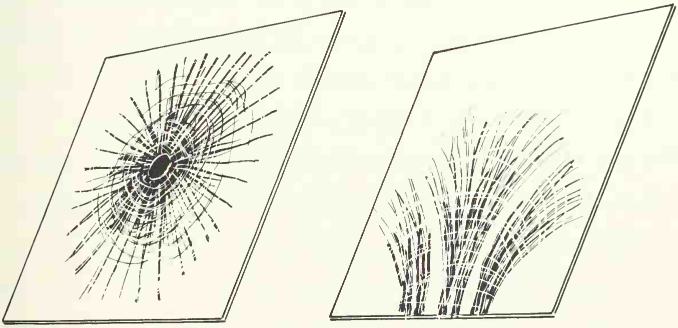
Applying the tension once again, we find that the metal will stretch until it grows visibly thinner near the middle. Finally at 60,000 pounds per square inch, more or less, the piece breaks with a loud crack! That 60,000 figure gives you the tensile strength of your sample. It is abbreviated to "psi" or "p.s.i.": pounds (per) square inch.

Obviously the tensile strength of steel in a cable that is designed to lift such things as a steel beam or an elevator is of vital importance.

Glass is not ordinarily used in place of a cable or wire. However, you know tensile strength is involved when you think of a bottle filled with a carbonated drink; or of a large mirror hanging from studs run through holes that have been bored through the glass itself; or when you consider glass piping used in food or chemical manufacturing at high pressures.

But tensile strength is only one point involved in answering the question: "How strong is glass?" If the kind of test just described for steel were made on glass, we would find that glass, unlike metals, will not stretch! There is no significant permanent deformation after the application of tension; glass will break before it ever shows any sign of stretching.

The behavior of glass under stress is peculiar in other ways, too. A slight scratch on its surface will frequently be the point of origin of a break even though the break was actually caused by a blow in some other area. Or a scratch may lead to a complicated pattern of fractures. The vast importance of surface smoothness to glass strength is demonstrated in experiments with extremely fine fibers of glass.



All glass articles start with either a "gob" or a "gather" of molten glass. As soon as a fine fiber has been drawn like taffy, from a gob, it is extremely strong. Fibers a few ten-thousandths of an inch in diameter have been tested to destruction and found to support up to 1,000,000 pounds per square inch.

If it were possible to make a one inch square strand of glass with this kind of strength, it could hold aloft a whole parking lot of automobiles: 500 automobiles of 2,000 pounds each! That is far stronger than anything else we are likely to know. But unfortunately the fiber's strength is very short-lived. Even if the fiber is stored in a vacuum and never touched except at the ends, its strength decreases with every tick of the clock. Within a few hours its strength drops to something like two-thirds of its original value. Some kind of automatic deterioration takes place that is not completely understood. Even worse, if fingers—no matter how clean, and entirely free of any apparent dirt or abrasive,—are merely drawn over the sides of the fiber, its strength can be reduced to five percent of its original test.

Weathering, too, takes its toll. For fibers that were made in 1893 though very small (averaging .016 inches in diameter) had lost so much of their strength in less than forty years that they tested an average of only 8,400 pounds per square inch. The same effect occurs with glass rods one quarter inch in diameter and in other glass forms. If it did not, we might long since have substituted glass fibers for steel in the cables of our suspension bridges.

For equal volumes, most glass weighs far less than steel. Soda-lime glass: density .089 lb. per cu. in. Carbon steel: density .283 lb. per cu. in. If in addition, it were stronger and as durable, bridges might look as though made for butterflies and angels rather than trucks, trains, buses and bumper-to-bumper loads of automobiles. Will science someday find the answers and make such dreams come true?

Experts believe that surface cracks develop in all glass shortly after it has cooled to room temperature, and that these cracks are the cause of the quick decrease in tensile strength such as in the fiber mentioned above. An experiment that bears this out is the one in which glass samples are polished by repeated immersion in acid and frequent washing: the tensile strength is greatly increased. This kind of polishing removes some of the surface and eliminates many of the scratches and cracks. The reverse is true, too: deliberately or accidentally made surface scratches greatly weaken the glass.

Wherever there are scratches in glass, very great stresses occur. These are immediately around the scratched area. Because glass has no plasticity (it can't "give" here and there in response to stress), the only way that such stress can be relieved is by the creation of new surfaces. New minute cracks extend from the first scratch and tend in turn to increase the imperfections already made. If a ball hits a window where it has been scratched, it need not hit very hard in order to crack it completely: the cracks extend very rapidly—as much as 5,040 feet per second.

Different kinds of glass and different kinds of treatments in their manufacture will produce articles with widely varying characteristics. The maker of soft drinks, soda water, beer or champagne must have bottles that will withstand pressures of up to 200 pounds per square inch. Of course they must also be tough enough to stand a lot of banging together and rough handling everywhere they go, from the glassmaker to the bottler, wholesaler, retailer, restaurant or home.

When bottles are returnable, they have to stand thousands of bumps and scrapings, one against the other, and still more thousands in undergoing sterilizing, refilling and capping operations. Look at an old returnable bottle and you'll see the results of age in nicks and scratches. Think how many times stronger such a bottle must be than bottles that are to be used just once and then thrown away! Think how fragile by comparison is a thin, artistic wine or water glass created primarily for beauty and only secondly for utility.

Perhaps one of the greatest demands for strength in glass is in its use in insulators for high-voltage power lines. When you see a whole string of insulators, the one on the bottom attached to a heavy cable may be at the end of a span of 1,000 feet or more. These glass insulators have to support the weight of the cable itself plus snow and ice that may accumulate on the cable and weigh as much as or more than the cable itself. In addition, the glass insulators have to take the buffeting, the jerks and jolts of the cable as it whips in high winds. At the same time these special shapes of hanging glass must perform their main function: insulate the cable and prevent the escape of electricity from one cable to another or to the wooden or steel towers and so to the ground. What a contrast such rugged glass is to that beautiful, fragile wine goblet!

A piece of glass that will withstand terrific tension for five seconds will often break with half that amount of tension if such a half weight is left hanging overnight. All materials lose strength when subjected to steady tension over a long period of time. But the effect is especially pronounced in glass. Evidently defects, weak spots in glass, that will extend at the rate of 5,000 feet per second when breaking under heavy stress will also slow down to a snail's pace under light loads that they must endure for a long period of time. The result is that glassmakers and engineers always specify great thickness, great margins for error in glass that is to carry mechanical loads. According to some experts they probably overdo it in the name of safety. (It is interesting that although the gradual failure of glass under stress is more pronounced than in metals, old glass does not fail and break, no matter how old, when it is *not* stressed or loaded, yet pure metals *do* fail when old, without any tension at all.)

We all know that glass is hard. But people have different ideas about how to measure hardness. We believe that when we press a fingernail against one piece of wood, then another, we can tell which is the harder. When professionals use machines, they press a particular shape of hardened steel against the material to be tested and measure the distance the material "gives" in permanent deformation in relation to the amount of pressure brought to bear against it. Such tests work very well for wood or for metals. But for glass they are not entirely satisfactory. If the testing machine happens to be placed over a minute air bubble just beneath the surface of the glass, or directly over a major crack or scratch, the glass surface will crush far more quickly than it would otherwise. It will not be indented by pressure (as metal would be) any more readily than it will stretch. It crushes and breaks. So the measurements of "hardness" are not very satisfactory.

We know that different kinds of glass will scratch more or less easily, and scratch resistance, which is another kind of measure of hardness, is important to any estimate of the usefulness of glass. Here, too, exact measurements are difficult. If you scrape the surface of a piece of glass with the corner of another piece of glass of the same kind, the depth of the scratch will be determined by the pressure you use and the speed with which you draw the sharp point over the surface of the glass. Why? Because rapid movement of the sharp point over the glass surface will develop so much heat in the point that it very quickly softens and becomes dull.

We do know, however, that some kinds of glass are far more scratch-resistant than others. The beautiful, sparkling, so-called "crystal," much used in quality tableware, is likely to be glass that is made with lead oxide as one of the ingredients. It is one of the softest, least scratch-resistant of the glass types. You can easily see this if you look at a fine drinking glass or tumbler that has been often used with a glass stirring rod or "muddler": the scratches on the inside of the glass were made accidentally with only the slightest pressure. On this kind of glass you may find that the bottom has been scratched on the outside simply by ordinary movements of setting the glass down on a table. In other words, one kind of glass can be very hard and scratch-resistant while another is very soft.

Another characteristic of glass is thermal endurance, or the ability to withstand high temperatures and rapid changes from high heat to low.

Ordinary milk bottles, ordinary jelly glasses, heated to water boiling temperatures, will break if you fill them with cold water. But Pyrex chemical laboratory equipment will withstand amazingly rugged treatment, from ice-coldness to boiling temperatures. The story of Pyrex is dramatic.

At the beginning of this century, an express train was speeding through a rainy, windy, night. As it approached a station a signalman stepped forward with his red lantern to warn the engineer. There was danger ahead: a slow freight was approaching on the same track! As the signalman waved his lantern, cold raindrops hit the hot glass. It shattered to bits and the rain put out the lantern flame. The signalman shouted but, his voice unheard, the train roared past to a head-on collision with the freight.

Such horrors on the new high-speed railroads made the search for thermally tough glass urgent. Scientists at the Corning Glass Works took up the challenge. Dr. Eugene Sullivan, who had established the research department there, found that glass made with the addition of some borax (a compound of sodium, boron, oxygen plus water) resisted temperature changes far better than ordinary glass. Unfortunately, though, this kind of glass was so weak that it would deteriorate even in plain water!

Sullivan was soon joined in this early industrial research department by William C. Taylor, a young chemist from the Massachusetts Institute of Technology. Together they tried one formula after another—largely by trial and error, for on this kind of problem there was little experience. What they were searching for was a mixture of boric oxide and silica sand that would have the lowest possible rate of expansion with change in temperature and the highest possible chemical stability—the two requirements that would help glass resist thermal changes and also chemical deterioration.

By 1912 they finally found a combination that worked. Corning began making lantern globes and battery jars of the glass they called Nonex. It cut down the breakage of lamp globes by 60 percent and doubled the life of glass battery jars, which in those early days of the telephone and telegraph were filled with acid.

A few months later Dr. Jesse T. Littleton joined the Corning research group. Not long afterward he asked for part of a battery jar with which to test an idea he had: the new glass might make a good baking dish. Next day the scientists were treated to a cake that Mrs. Littleton had baked in glass. It was delicious, and the men began a new search for better and better glass destined for the ovens of the world.

In 1915 Corning introduced their first glass baking dish. They named the amazing new glassware Pyrex. From this beginning has come all the other glass kitchenware and the thousands of special glass products for chemical laboratories as well as other thousands for food and chemical manufacturers.

The chief reason for the success of this kind of glass is that it expands only one-third as much as ordinary glass when it is heated. To see why this is so important we have to realize that breakage by sudden, extreme changes of temperature is breakage by changes in both inside and outside tensions. If a rectangular bar of glass is slowly heated in your kitchen oven, to a point where inside and outside temperatures are the same at, say, 350° F., the entire bar will have lengthened according to the kind of glass it is. Indeed, each of its three dimensions will have increased proportionately. If the bar is then plunged into ice water at 32° F., the outer surface, will cool very rapidly and contract every part of that outer surface, which shrinks and tends to return to its normal dimension at 32° F. But the glass inside this outer "skin" cannot cool so quickly and remains far bulkier than the outside. This puts a terrific tension on the outer skin, for it is as though a glass envelope were trying to hold its contents while the envelope itself was growing much too small.

So it is clear that the tension on this outer skin will be far greater if the glass is the ordinary type with higher rates of expansion and contraction. It follows, too, that the quicker the inside of the bar is cooled, the sooner the tension will be relieved between the outside "package" and the inside contents. For this reason, odd as it seems, the thinner the glass, the less likely it is to break, for the thinner the glass, the shorter the distance the heat must be conducted to be dissipated, or evenly absorbed. Sudden heating of the glass is much less likely to break it than sudden cooling. For sudden heating tends to expand the “envelope” faster than it does its contents.

Because of the low expansion rate of Pyrex-type glass—it is far less than that of most metals—and because of its chemical durability, plus the possibility of grinding it to a surface that would have very few imperfections, this was the material that was chosen to make the huge disk, 200 inches in diameter, for the gigantic Hale Telescope at Mount Palomar, California. Remember that in this telescope, as well as in all other telescopes of this kind, the purpose of the disk has nothing to do with the transparency of glass. This disk was made to be a mirror with its reflecting coating, not on the *back* of the mirror like those in our homes, but on the exposed *outer* surface instead. For this reason the designers of the modern astronomical telescope can choose any material—transparent or not. But this low-expansion glass was their choice for the mirror that was to collect the light from stars trillions of miles away and bring that far-off light into perfect focus for the human eye and for the camera, with no interference from changing temperatures.

The first big disk was spoiled by the failure of a part of the mold. But the second one, cast and then carefully and slowly cooled over a period of months, was crated in steel and sent to California by rail.

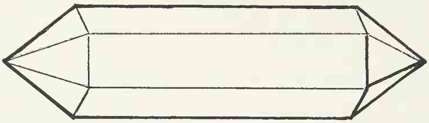
Because glass has been made to expand and contract to the least possible extent, man, looking out at the stars from the peak of Mount Palomar, can see four times farther into space than ever before.

# 7. The Materials of Glass

In Chapter 5 you read about some of the proportions of materials in various kinds of glass. For all the usual kinds of glass, sand is, of course, the major constituent. Any sand from any source *could* be used. But to make good glass, it is far less expensive to use a sand that, as it is produced by nature, already comes close to the ideal. That way, handling the sand is cut to a minimum. Eliminating impurities, either physically or chemically, and even grading and sifting it for the right particle size can be expensive.

What is ideal glass sand? Where can we find it?

To begin with, ideal sand would be pure silicon dioxide ($SiO_2$) in precisely the size particles that would melt most easily and mix with other ingredients most readily. Pure quartz is pure silicon dioxide and occurs in crystals of hexagonal form, with ends of hexagonal pyramids:



Actually, completely formed crystals of quartz are not too common in nature. When quartz is pure, it is transparent, colorless, and is known as "rock crystal." It is valued as a gem stone. But in its impure forms—mixed with other minerals—it can be white, yellow, brown, pink, green, blue or black. The crystalline, colored forms of quartz and those including other minerals are known as rose quartz, blue quartz, amethyst, smoky quartz, milky quartz, cat's eye and tiger's eye. If you are a "rock hound," an enthusiast about stones, you will recognize some of the other forms of quartz. Some are composed of such small crystals that it requires a microscope to see them. Among these are chalcedony, carnelian, jasper, flint, chrysoprase, agate, onyx, sardonyx and chert. The opal is a noncrystalline form of quartz that contains 3 to 9 percent of water. All these quartz forms are primarily silica (the common name for silicon dioxide) with various kinds of impurities in small amounts.

Quartz is one of the commonest minerals in the earth's crust, forming about 12 percent of the solid part of our planet, and it is very widespread. While gem and semiprecious stones are most interesting, they are a small part of our quartz supply. The great bulk of our quartz is contained as parts of our igneous rocks and sandstone. The igneous rocks are those that have been formed in the ancient past when they crystallized after cooling from the molten state like lava from volcanoes. Some of these rock forms are known as feldspar, mica, hornblende. But the one you are most likely to know is granite. When granite was formed, the quartz in it crystallized slowly. The result was that the crystals are large and the varied structure that makes granite such a handsome building material is coarse-grained.

What has this to do with sand? Well, rock may look permanent, and measured by our short lives on earth, it does seem to be. But in terms of centuries and eons, rock is perishable, too. Water from the skies will penetrate little crannies in the rock. When water freezes, it expands—as you know if you have ever seen a bottle of frozen milk—and ice will break off larger and larger pieces of rock. Gradually each piece of rock becomes smaller. Also, the pressure of tiny roots of growing vegetation does the same kind of thing. And the rain water we think of as being so pure is not really: it absorbs some of the carbon dioxide of our atmosphere and becomes a weak carbonic acid. We drink it happily, wash and swim in it without harm. But in contact with some of the silicates, weak carbonic acid eats away at granite, leaving a mixture of pure silica, a clay known as kaolin, and a salt. In some areas, rivers will be murky with clay that has been washed away from the granite. Gradually large stones roll to the river valleys, and smaller and smaller pieces are made of them by both physical and chemical action. Then, with each new spring freshet, small pieces of silica (quartz) are carried farther and farther downstream. Eventually, as the river grows wider and currents are slower, only the clay and the smallest pieces of silica are carried on, while the heavier pieces become beds of sand, one layer on top of another as the years go by. Eons later, such a sand bed may be found intact and used to make glass. Or, if left alone, it may continue to be built deeper and deeper until the sand is cemented together by chemicals in solution in the water, forming sandstone. This, too, may be used in making glass, for sandstone can be fairly easily ground, washed, and sieved to become sand once again.

Where do glassmakers find their sand? The chapter about glass chemistry told of some major deposits. Then there is the story about an early American glassmaker who offered a reward to anyone who could give information about a sand deposit of value, for he had used up his local supply and now had to haul sand over greater and greater distances. He might have saved himself a great deal of effort and expense if he had only known: an underground deposit of exceptionally fine sand was found directly below his factory! He used it, of course, and today some of the finest known sand deposits lie deep under the surface of the earth where they are mined and shipped to factories very much as are metal ores.

Chemical purity in sand is important, as you already know. Where iron oxides are present as coatings on the surfaces of quartz grains, it has been found that removing the smallest grains decreases the proportion of impurity in the remainder. Why? Because the surface of one large grain is smaller than the surfaces of 100 small grains that equal the weight of the single large grain. To illustrate, let's say that 100 ping-pong balls equal the weight of one baseball. It is easy to see that it would take a lot more paint to cover 100 ping-pong balls than it takes to cover a single baseball. This explains why the smallest grains of sand are sometimes discarded.

Handling quantities of sand becomes a major problem in large plants. Such plants melt 100 tons of glass a day in each of their continuous-melt tanks that work around the clock. Everything is used, from a shovel and wheelbarrow to large conveyor belts, to make the handling easiest and most economical. Special covered freight cars are built to protect sand from contamination in transit. Even tank cars are designed for sand, unloading from the bottom by means of large, motor-driven drag chains that carry the sand to a central bottom port. But even with all the special equipment, nails, nuts and bolts, grain, sticks of wood somehow get into the sand and must be screened out.

Screening, weighing and mixing the sand with other components and transporting them all to the melting tanks, or pots, may include everything from completely automatic, push-button operations for large plants to intricate and skillful hand operations used during experimental melting in laboratories.

In any art, craft or science there are always special precautions to be taken in handling materials. Glassmaking is no exception. Sand that is too moist will freeze into a solid block at low temperatures. Some materials such as soda ash (source of $Na_2O$) will absorb water vapor from the air and become lumped unless they are handled properly and used before long exposure has caused such hardening.

The new material that goes into the batch for melting is supplemented by scrap glass of the same kind as that being made. It is called cullet, from the word cull, meaning "to separate." The source of cullet is the faulty glass that, because of its poor appearance, or breakage, is separated from good products in the factory. Cullet is crushed and ground before it is mixed with the other ingredients. In some cases the amount of scrap glass is more than 50 percent of the batch. It is used in much the same way as scrap iron is used in the steel industry. But where one plant makes more than one kind of glass, separation poses another handling problem.

The quality of glass is, like that of a cake, determined in part by the accuracy of measurement of the materials. In large glass plants, automatic scales close the gates at the split second that the correct portion of any ingredient has flowed from a hopper into the batch for mixing.

The mixing of materials is usually done in rotating barrels that work in the same way as the concrete mixers we see mounted on trucks wherever new building is going on.

Finally, when the materials are properly measured and mixed, they are sent to the furnaces for heating and melting.

The sources of some of the other constituents of glass are interesting, too. The major components are available in large quantities in many parts of the world, and as a consequence are relatively inexpensive.

Sodium oxide is one of the chief ingredients of many kinds of glass. Common table salt is one of the most widespread salts in the world, but in glassmaking it cannot be used directly as a source of sodium oxide because it volatilizes at white heat and flies away as a gas. It will not react with silica (sand) except in the presence of steam. And steam, of course, would be an unlikely companion for molten glass when its temperature is six times that of boiling water—and more. So two other salts are used instead. Sodium sulphate is one. It is found in natural salt deposits in the western states, and is also made by chemical conversion of common salt. Its common name among glassmakers and dealers is "saltcake." The second source of sodium is sodium carbonate. It occurs naturally in some alkaline lakes of California and Nevada. "Soda ash" is its common name, which comes from an old way of producing it: burning seaweed and collecting the ash.

Calcium oxide in glass comes from calcium carbonate, which is the main chemical composition of many rocks including marble, limestone and chalk. Limestone is the primary source of calcium carbonate. It is this ingredient that gives its name "lime" to silica-soda-lime glass.

The above materials are of major importance in the output of glass.

Potassium oxide can be used in place of, or together with sodium oxide. Used alone, it produces a brighter, better colored glass that is generally harder and has a higher melting point than soda-lime glass. Potassium oxide is found in some lakes of Nebraska and California, and in Great Salt Lake, Utah. It is used, as a rule, only for special glass such as lead "crystal" glass, "Bohemian" glass and optical glass. The potassium-oxide salt is highly deliquescent (absorbs water vapor from the air); if left open to the atmosphere, it very quickly becomes a pasty, wet mass and soon forms a watery solution.

Here are some of the other oxides of importance: Boron oxide comes from borax or boric acid. Aluminum oxide, which is known as alumina, is usually used in the form of feldspar. But it is interesting to note that such gems as topaz, the sapphire and the ruby are nearly pure forms of aluminum oxide. (It is suggested that you keep them as they are!)

Magnesium oxide is added to the batch (whether you want it or not) whenever burnt lime is made from dolomite, one of the minerals used to supply calcium oxide. Lead oxide is a pale yellow powder made by spraying molten lead into a high-pressure stream of air. It is known by the common name of litharge, and though many kinds of glass are colored, this is the only one of the important ingredients of glass that is itself colored! Stranger still, this yellow powder is the distinguishing contributor to our best *colorless* glass: lead "crystal" glass, so much used as art glass and as the finest glass tableware.

Barium oxide is produced chemically in a reaction in the glass melting process whenever barium carbonate is used in the batch. Zinc oxide, used also in glassmaking, is a white paste the doctor puts on a cut or a mean scrape when he wants it to stay moist as it heals, instead of drying out and cracking open. It is made by treating metallic zinc directly: heat it until it vaporizes, burn it in air, collect the ash. It will be yellow when hot, but white when cool.

While the above are only a few of the important compounds used in making glass, every one of the ninety-two elements has been tried at one time or another in compounds that have gone into experimental glass formulas. And experiments go on and on!

# 8. About Furnaces, Pots and Tanks

As you already know, the first furnaces were volcanoes and the first glass used by man was already fused, cooled and ready-made for him when he found it.

When men started to make glass on a scale we really know anything about, they mixed their batches of materials, put them in small clay pots and heated the pots for many hours with constantly tended wood fires. Finally the raw materials would melt and fuse, forming a glassy syrup. That it took a lot of work and a lot of fuel to do this is evident when one knows that the temperatures required for melting and "plaining" glass—getting rid of gas bubbles and impurities—run from 1250° C. to 1700° C. Even at the lower of these two temperatures, iron is not just "red hot," but is even hotter: yellow to a very light yellow. At anything above 1540° C., iron is a still hotter, dazzling white. So you can see that it would take a great deal of fire to get up to the 1250° C.—the minimum heat required to make glass.

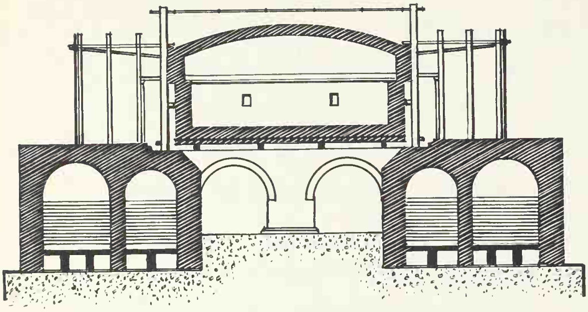
Gradually, men learned to build furnaces that would produce heat more efficiently. Temperatures were better controlled and furnaces came to look like giant beehives. The clay pots glassworkers used grew bigger, too, each holding a few hundred pounds of glass, and each furnace built held more pots, clustered in a ring around a central source of heat.

As years went on, wood naturally became scarcer. It was consumed in ever larger quantities for both metals and glass. Coal was finally substituted for wood. Then gas made from coal began to replace the direct use of coal itself. With these changes fires were bigger and hotter. So furnaces became bigger yet, and whole tanks of glass were melted at one time.

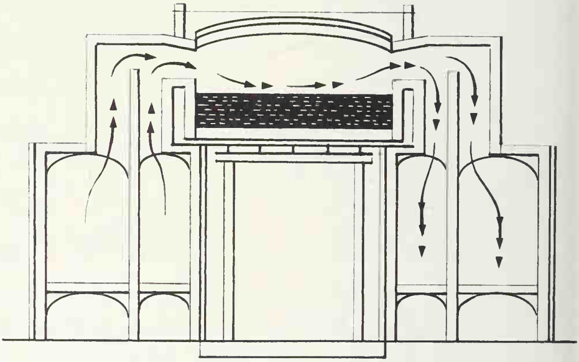
By the middle of the last century, Charles William Siemens, an inventor who was a naturalized Englishman of German birth, became interested in the reverberatory furnaces that were then being used. In this case, "reverberatory" simply means "reflected," for the flames were directed in sheets as close as possible above the tanks of glass so that the radiant heat was reflected from the low, arched roofs built of special bricks over the tanks. When Siemens began to investigate, he found that after the flame from one end of the furnace had been led over the "charge" of material to be melted, the hot gases were simply allowed to go up the chimney "to heat the whole outdoors."

Siemens' brother asked him, "Why not use that heat to preheat the gas and the air before they are piped to the burners at the melting end of the tank?"

Acting on this suggestion, Siemens built four large



Siemens' tank furnace. Air is heated in outer compartments of firebrick, gas in inner piles of brick. See the course of air and gas and the exhaust gases in diagram below. Direction of flow is reversed periodically.



The batch of materials is fed into continuously burning furnaces at one end of the tank, and liquid, molten glass is withdrawn from the other end.

chambers and put great piles of firebrick in them arranged so that there were large checkerboard gaps between them. Instead of letting the hot gases go directly up the chimney, he forced them with blowers through two of these chambers for perhaps half an hour, heating the bricks as much as possible during that time. Then, reversing the direction of flow, he led gas through one of the hot chambers, and air through the other hot chamber. When hot gas and hot air pipes met at the burners in the furnace, the gas and air delivered a flame with the most nearly complete combustion possible, and with far greater efficiency. This returned much of the heat to the furnace.

Meantime, the exhaust gases were led through the other two chambers for half an hour to be heated and reversed in turn in regular cycles.

It was about 1860 when Siemens' first furnace was put into use. Though innumerable improvements and variations have been made on it, the Siemens model is still the prototype of today's glass furnaces (except for the electric furnace). It marked the world's first major advance in furnace efficiency. Soon tank furnaces were made that operated day and night, seven days a week. New materials are charged at one end of the tank while molten glass is taken out at the other end in a continuous operation. Some tanks operate two and three years and even longer before they have to be shut down for repairs.

The size of the furnaces and the tanks has grown and grown. Today the largest of these are tremendously long and, when full, hold hundreds of tons of molten glass and glass materials. These are in every stage of melting and "fining"—the word that is used for the final operation within the furnace when the last tiny air and gas bubbles break out of the top surface, leaving the glass that is the best possible for its purpose.

Unless you have watched glass materials melt (through dark glasses to protect your eyes from the brilliant flame), you may think that it is a relatively calm process, like boiling up a pot of water or soup. It isn't. Sodium carbonate melts at 853° C. and potassium carbonate melts at 885° C. But, like some metals mixed in the right proportions, the two compounds together will melt at a lower temperature than either one heated separately. The name applied to this phenomenon and the particular low temperature at which such combinations will melt is *eutectic*. For these two compounds, mixed in equal molecular proportions, the eutectic melting point is 690° C. That is 163° lower than the melting point of the sodium carbonate, which is the lower of the two.

Knowing this, you might expect that these two compounds in a mixture of glass materials would fuse first. They do. Then, as the temperature goes up, the silica goes into solution with the various components, and the mass is *violently* agitated by escaping gases that aid in the complete mixing together of the materials.

When fusion is complete, time in the furnace must still be allowed before the glass can be used. Much of that time is used in freeing the "melt" from bubbles. Because large bubbles have greater buoyancy than small ones and collect little bubbles on the way to the surface, one of the aims of the fusion process is to have it proceed as rapidly as possible. It is in this stage that the most gas is produced, and the transfer of heat to the melting materials at a very rapid rate is a great advantage here. Any furnace that does this serves well. For if the melting proceeds too slowly, there comes a point at which the large bubbles have all escaped, leaving the glass still full of very small bubbles and "seeds" that go out very much more slowly—and expensively—even though much higher temperatures are eventually reached. "Seeds" and "stones" are parts of the mixed materials that have not yet been dissolved in the hot "syrup" of molten glass.

These are some of the reasons why the rapid, efficient heating of Siemens' furnace and the many improvements since his day fill glass manufacturers' needs very well indeed. Yet scientists are still looking for more efficient furnaces, and no doubt will be for many years to come.

It doesn't take much thought to realize that you couldn't put sand, soda and limestone into a kitchen pot and heat it over a burner to 1500° C. the way you heat water to the boiling point at 100° C. The pot and its contents would be an unholy mess in no time, for aluminum melts at about 658° C., cast iron melts at about 1230° C., 1 percent carbon steel melts at about 1470° C., and at red heat (about 800° C.) nearly *any* metal pot would begin to sag under the weight of your batch; at yellow heat, around 1200° C., such a pot would be unmanageable. In addition, the aluminum or iron would enter into chemical combination with some components of the batch and make the glass unusable even as cullet.

You can see, then, why special fire bricks or blocks made of "refractories" are used to make the tanks and the walls of furnaces, and why special clays are used to make the glass melting "pots." Refractories are composites of several minerals. (The word "refractories" comes from "refractory," meaning unyielding, unmanageable and therefore, in this sense, resistant to melting, resistant to heat, and hence hard to fuse.) The principal materials used contain silica and aluminum oxide, much smaller quantities of titanium oxide and other oxides. A whole separate industry is engaged in making refractories.

There is more than one reason why the furnace flames are blasted *over* the melt. The radiant heat of the flame passes directly from the flame to the materials of the melt and in addition, it is reflected from the arch or "crown" built above the tank. That reflected heat passes *through the flame* to the melt. Here's why:

Glass does not conduct heat very well. You know how hot a silver spoon gets in a cup of hot coffee. Silver is an excellent conductor. But if you put a glass stirring rod or a glass tube into the same cup at the same time, you can hold it very comfortably. Bad as it is as a conductor, however, nearly all glass allows the passage of *radiant* heat quite readily. If you have ever ridden past a big trash fire alongside the road with your car windows closed, you may easily have felt the heat. It was the radiant heat that passed directly through your closed window. Or hold your hand near but not *on* an electric light bulb. This illustrates the same thing. The glass permits the radiant heat to pass through the glass from the incandescent filament in the same way that light passes.

In a glass furnace, radiant heat penetrates the glass melt especially well when the flame is a luminous white or yellow flame such as you see in a trash fire or in a domestic oil furnace, rather than the light blue flame you see coming from the oxyacetylene welding or cutting torch. Spreading this heat evenly over the entire tank—heating adjacent areas at exactly the same rate—is very important, for uneven heating will produce heat currents between hot and cooler parts of the viscous mass that can result in stringy, "cordy" glass. In the melting end of the tank, uneven heating can produce seeds and stones, and can be the cause of the loss of decolorizing materials or the loss of an important flux that makes melting easier. This can result in glass that is not uniform throughout and sometimes unusable.

In addition to very careful handling of the furnace flame, glassmakers pay a great deal of attention to the materials of the batch to produce homogeneous glass. One of the ingredients may be added for the sole purpose of producing gases quite late in the melting process so that the plaining or fining operations may be started earlier—during the melting—and carried on longer before the glass reaches the point for forming operations to begin.

Another component may be added so that greater fluidity of the molten mass may be obtained. Making it less viscous, and "thinner," will facilitate the rising of bubbles, both large and small. Naturally, the addition of any of these "special purpose" ingredients must not alter the character of the glass appreciably. The glass must not become too difficult to form at working temperatures; it must still be adequately resistant to chemicals; and it must, in its final form, retain the physical characteristics required.

When Siemens made his contribution to the glassmakers' art about 1860, the number of materials commonly used for glass was limited to about five or six except for those used for color. There had been little change in basic materials in 3,000 years!

But not long after Siemens, Otto Schott, a German, started working with glass. His primary interest was in optical glass. He and his associates at Jena, Germany, added more than twenty-five new elements for use in glassmaking and succeeded in making optical glass that was vastly superior to any that had ever been made before! The result was that until we were forced to make optical glass during World War I, we imported it all from Germany. But when our supply was cut off, our manufacturers came through with flying colors, making optical glass that has never been surpassed in quality.

Even today optical glass is frequently made in pots. For very special optical glass, only one pot is permitted in a furnace. This is because the temperature of a single pot can be controlled far more precisely than the temperatures of two or more pots heated at once. And temperature control can make or ruin an extremely expensive batch of material for optical glass. For that material must be selected with the utmost care, analyzed with the greatest precision and handled with superb skill from beginning to end.

When glass is at high temperature, it is extremely corrosive. The bottom of a pot will be melted and eaten away from a five-inch to a one-inch thickness after only a few months of use. So it is evident that the materials of the glass pot must be chosen with the same care as the raw materials of the glass formula itself. Why? Because parts of the pot itself become part of the finished glass, in spite of the greatest care and the finest equipment available.

From the earliest wood fire to the 1,000-ton tank furnace is a long, long way. Yet glassmakers have not reached their goal. They are still looking for more improvements in every step of glassmaking as it advances toward tomorrow.

# 9. Glassworking Skills

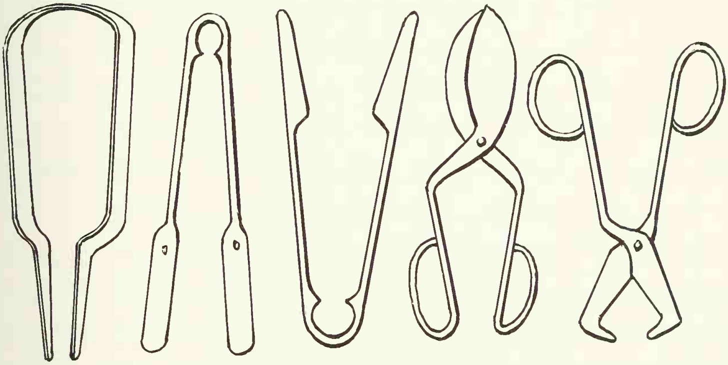
IN EARLIER CHAPTERS OF THIS BOOK YOU READ how the ancients are believed to have made hollow ware by covering a sand core with molten glass, and then digging as much of the sand out of the vessel as possible when the glass had cooled. While this method was replaced by the blowpipe, special cores *are* used to produce threaded glass such as those inside the glass insulators that are held on power-line and telephone-line crossarms by threaded pins.

Like the ancients, modern glassworkers still decorate their glassware by covering it with additional layers of colored glass. But such glazing or "flashing" is usually a process of putting a thin layer of colored glass on top of a heavier piece of colorless glass. This is the way that light shades of some colored glass can be made most readily. As you have read, a thick piece of glass may appear to be absolutely black, while a thin section of the same glass proves to be purple or violet. To achieve a thin layer of colored glass on top of colorless glass, a small bulb of the colorless glass is blown, dipped into molten colored glass, and then the entire bulb is blown to a larger size. This spreads the colored glass over an increasingly large surface, thinning it just as much as if you rolled it out with a rolling pin on a flat board.

You have read about the importance of the invention of the blowpipe and what it did for the art of making glass. It is interesting to note that no other material lends itself so well to hot forming in this way. This is why:

Look first at the way the blowpipe is used. A simple iron tube about four or five feet long, it has a mouthpiece at one end and a knob at the other, and, so far as anyone knows, it has changed very little in shape from the time that it was first used some 2,000 years ago. To use it, the skilled workman lowers the pipe to the surface of the molten glass in the pot or tank, holding it almost horizontal and twirling it slowly to pick up a "gather" or "gob" of glass. He takes his gob from a spot in the pot or tank where impurities have been skimmed off, estimating carefully the amount of glass he needs for the article to be made. If the glass he is using is a lead glass for a goblet, for instance, the temperature as he takes it out of the pot will be about 1000° C.; the mix will be a thick, viscous, bright red mass. At this temperature, twirling the blowpipe on the surface will pick up the glass, for it will stick to the iron and stick to itself. At very much *higher* temperatures it is difficult to make a gather at all, because the glass is too thin, too liquid. At temperatures much *below* 1000°, the glass is so thick that gathering is very difficult, and getting just the right amount on the end of the blowpipe is almost impossible.

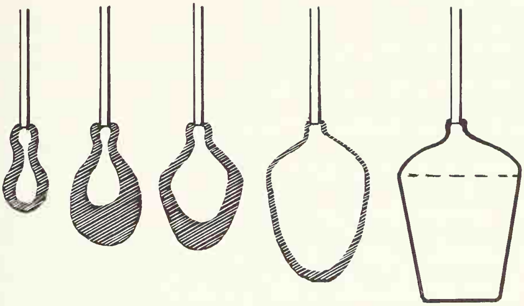
Glassblowing, as in the making of special tableware and various kinds of art glass, is not a one-man job, but the work of a group of five to seven men. This team of men is known as a "shop." The head of the group, who is responsible for the quality of the work and who does many of the most difficult parts of the job, is called the "gaffer." There may be many shops that take their molten glass from one furnace, but each shop has its own tools, its own benches and glassmaker's chair with the special long arms you'll hear more about. Each shop has its own small reheating furnace too—known as a "glory hole"—for reheating work in progress is frequently necessary. The tools, by the way, are very little changed from those of the Middle Ages, although the blowpipe then was probably shorter than now.

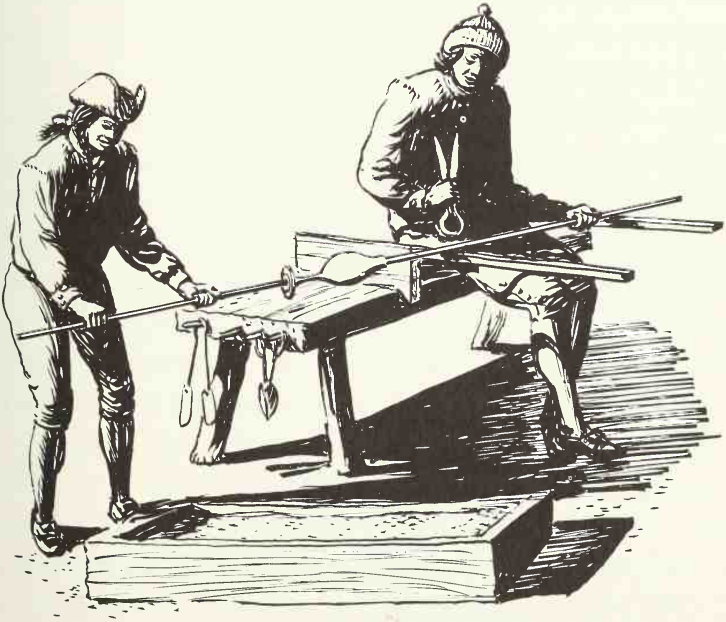


Glassmaking tongs and shears.

After the gather is made, the pipe is rolled back and forth to shape the mass into a symmetrical form, cylindrical for one type of thing, or conical with the thicker end *at* the pipe or *away* from the pipe according to the shape that is going to be blown. Shaping is important, for a heavy, immediate puff of air into the very hot glass in an irregular form can easily blow a hole right through the thinnest section. So the gob is shaped not only by rolling the pipe, but also by rolling it and pressing the mass at the appropriate places with a wooden paddle so as to mold it and keep the gather centered on the pipe. At the same time, the outer surface of the gather is being chilled and toughened by the air, and the gather may be rolled on the "marver" both to shape and cool it more. (The word marver comes from the French for marble, *marbre*. The marver today is not marble, but is usually a piece of cast iron that has been machined smooth.) This gives the outer surface of the glass a smooth layer of more viscous, tougher and more resistant skin than the interior, and it contains the still extremely hot and fluid glass within it.

Once the glass is centered on the pipe and roughly shaped, the gatherer puffs lightly into the mass for the first time, knowing that the bubble that forms will develop in the *center* of the gob. The air that he blows into the center creates an *internal* skin, somewhat like the outer skin but, of course, much hotter and hence softer. Now, holding the pipe aloft, or lowering it toward the floor, he can control the direction of flow of the more liquid glass held between the inner and outer skins. By gravity it will flow toward or away from the pipe, making the thickness of the walls of his bubble greater or less near the pipe or away from it, according to the way he holds his pipe as he blows.





Steps in making a tumbler. Dotted line indicates where glass will be cut with shears.

The glassmaker's chair has long arms covered with steel. By rolling the pipe on them, and pressing the tools against his bubble of glass, the workman shapes it to the form of the bowl of the goblet he is making, for example. When ready, another workman brings a new gather. It is "dropped on" the base of the bowl where it adheres solidly much like welded metal. By more rolling, shaping with tools and reheating, this new addition becomes the stem of the goblet. Another gather, added to the stem, becomes the foot. Then a very small amount of hot glass on the end of an iron rod called a pontil and nicknamed "punty," is pressed against the center of the foot, where both the glass and the punty adhere firmly. Next, using the punty as a handle, the goblet is now cracked away from the blowpipe so that the whole goblet-to-be is now held by the punty alone at the center of the foot. Held this way, the workman rolls the punty on the chair arms as he did with the "blowing iron" or blowpipe. And as he slowly rolls the punty and glass, he cuts the rough top edge where the blowpipe had been attached with a pair of shears. It looks almost as easy as cutting a piece of molding clay, for the hot glass is still very soft and yielding. If the rim needs further smoothing, it can be done with one of the tools held against the rim while the glass is rolled, or the rim can be heated again until the thin edge just begins to flow. Then, while one man holds the goblet upright in a two-pronged wooden fork placed around the stem just below the bowl of the goblet, another man strikes the punty a sharp blow near the foot of the glass. Since the glass at the foot and at the punty have both cooled, it is fairly brittle, and the two are cracked apart. The goblet is carried to the annealing oven, known as a "lehr," to cool slowly, relieving any strains so the goblet will be as strong as possible. When cool, the mark of the punty-to-foot weld is ground away, leaving a circular depression at the center of the foot that is one of the identifying marks of handmade glass. (This is not a foolproof distinction, for some glassware may be partially machine-made and only hand-finished and sometimes the poutil mark is left rough.)

Before describing the use of the blowpipe, we said that no material other than glass can be formed so well in this way. Perhaps you discovered why as you read about the technique. It is the fact that glass develops that tough, viscous layer or skin both inside and outside the bubble as it is blown, containing the still hot and fluid glass within these strong walls. Metals will not do this, because they do not grow more and more viscous as they cool. They harden all at once, when the entire mass reaches the same critical temperature. Red-hot iron can be *hammered* into shape, but it is not liquid inside, like glass. Thermoplastics can be formed by placing an unfilled balloon of plastic in a hot form and blowing it up so that it conforms to the shape of the mold. In this way many plastic bottles are formed. Cold sheet metal is sometimes clamped in a form to be blown into conformity with the shape of the mold by a carefully controlled explosion on the side of the metal that is to be the concave side. But no material other than glass can be worked as glass is in "offhand" blowing. (*Offhand*, as you may have guessed, means *impromptu, extempo-*

*raneous,* even *improvised*, the way a speaker or musician may invent his performance as he proceeds.)

Glass is formed by blowing into molds, too. In 1838, this was the fastest way of making a bottle. One man, working alone, could make as many as eighteen dozen four-ounce medicine bottles in twelve to fourteen hours of labor. The modern bottle-blowing machine can make that number in just two or three minutes. (But more about that in the next chapter.)

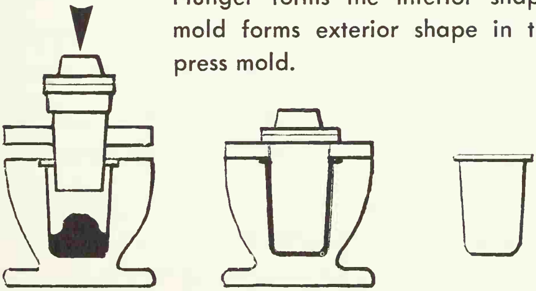
Where forms of hollow ware such as large, special-shaped bottles are wanted in small quantities, a hot-iron mold is frequently used in the old blowpipe method.

The mold is made in two halves that are hinged to close over a partly blown bubble of glass. The workman blows his bubble within the hot-iron mold. When the glass has filled out to the shape of the mold, the workman moves his blowpipe away from the vertical position and with a final, vigorous puff blows a balloon of thin glass above the neck of the bottle mold. He then breaks his pipe away from the bottle. Later on, the thin, ragged edges of glass above the neck are removed. Because of contact with the mold, bottles made this way are not likely to have the high sparkle and sheen of the offhand blown bottle.

The paste mold produces a bright, shiny bottle. But it has to be perfectly round, whereas the hot-iron mold can be square, oval, or irregular in other ways, including raised designs on the surface of the glass.

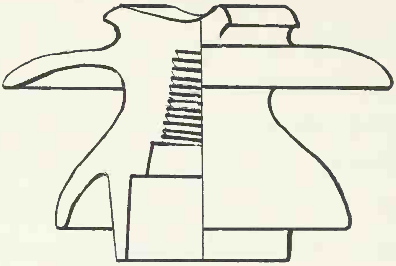
The paste mold is made of iron, too, but it has an inner lining of linseed oil and resin, or of soap or beeswax. The lining material is a heavy liquid that is brushed on the inside of the iron mold. The lining permits the turning of the glass bubble in the mold as it is being blown, and as the mold is always wet down with water before being used, the hot glass rotates against a cushion of steam wherever it touches the lining. The steam escapes through carefully placed vents. These molds are made in hinged halves, and all of them are more or less bottle-shaped. One of the big advantages of the paste mold is that no seam mark is made because of the rotation of the bubble as it is being blown. Another advantage is the bright surface of the bottle. And still another is that the lining protects the mold from wear.

The cup, or bowl, section of stemware such as goblets and wine glasses can be made this way, and finished by handwork as described above. Special chemical-laboratory ware and small quantities of special tumblers are made with paste molds, too.



Plunger forms the interior shape; mold forms exterior shape in the press mold.

Press molds of iron do not rely on blowing at all. A plunger forms the interior of bowl or plate-shaped glassware, and the concave mold into which the plunger fits forms the outside. The first company to make glassware in any quantity by this method was the Boston and



It takes a complicated mold to produce complicated shapes such as this glass insulator.

Sandwich Glass Company, about 1827, as you read in a previous chapter. The method is simple but molds become very complicated in order to permit removal of odd shapes such as glass insulators with wide "skirts." Basically, however, a gob of hot glass is placed in the bottom of the mold, and the plunger, lowered into the mold, squeezes the viscous glass up the sides of the mold and against the ring or collar at the top of the mold that forms the lip or rim of the bowl shape being made.

Tubing in small sizes can be made by blowing a long, thin hole into a gather, and then stretching the gather out. But this requires great skill and never produces accurately sized tubing throughout its length, which may be as long as 100 feet for very small diameters. Nearly all tubing today is made by machine, as you will read in the next chapter.

Casting glass in molds is almost always confined to articles of simple design. Glass will not "run" into small holes in a mold, for it is never so liquid as molten metal. In addition, pouring molten glass into a mold without including many bubbles is a very difficult technique.

The most noteworthy achievement in glass casting was the production of the glass disk for the telescope mirror on Mount Palomar, California. The largest single piece of glass ever made for any purpose, it is 200 inches in diameter, 26 inches thick, and weighs 20 tons. After this huge casting was made, the entire casting oven, holding both the mold and the molten glass, was heated up to 1350° C. for several hours in order to ensure the escape of any bubbles that might have been created when the glass was poured. Then it was cooled to 800° C. and lowered into an annealing oven where it was cooled to 500° C. But from that time on, the cooling process was extremely gradual and cautious. The disk was not permitted to cool more than 0.8° C. per day! The entire cooling process took a full year.

The reason for annealing and such gradual cooling is obvious when you realize that any glass product is likely to be made with sections of various thicknesses that would cool at very different rates if immediately brought from the manufacturing processes into room temperature. If this is done, such great strains are set up within the glass that it will break in the act of cooling, or if not just then, probably soon after the piece is put to use. Annealing is the answer. There is a temperature range for each kind of glass in which the strains set up in manufacturing will be relieved by the internal viscous flow for a matter of a couple of hours at, let us say, 550° C. Then the problem is to cool the glass at a slow enough rate so that serious *new* strains will not occur. The ancients used to do this by setting a newly made bottle or goblet in a relatively cool part of the furnace and eventually letting it cool off completely, but slowly, when the fires were allowed to go out. Today the annealing ovens do with great accuracy what the glassmakers of early times did mostly by guess and judgment based on experience.

Plate glass in America was made until about 1923 by casting molten glass on an iron table, rolling out the hot glass with a water-cooled cast-iron roller weighing as much as five tons, and then grinding the cold glass on both wides with finer and finer abrasives. It can still be done that way, but most of the world's plate glass is now made in strips that come from a continuous melting tank and stay in one long ribbon through the entire process of rolling, annealing, cooling, grinding and polishing. It is cut into standard sizes only when every other step is completed. The newest process eliminates the grinding by floating a strip of hot, newly formed glass on molten metal. The strip comes out of the continuous melting tank and is led directly onto the pool of molten metal, which gives it a bright, smooth surface on the bottom, and then runs the constantly moving glass under sheets of flame that "fire-polishes" the upper surface. More about this later.

There is one field of skilled handwork that has not been taken over by machines, and is not likely to be any time soon. That is "lamp working." It is the kind of skill that has created the glass menageries or Noah's Ark of glass creatures that have been popular for many years. Commercially and scientifically very important, however, it is the kind of skill that produces unusual laboratory equipment for chemists, pharmaceutical manufacturers, food researchers and many others.

One of the most unusual and beautiful collections of artistic and scientific value in the United States is the Ware Collection of Glass Flowers in the Botanical Museum of Harvard University. As an aid in the botanical study of flowering plants, the exquisite and accurate reproductions of 164 families of flowering plants are magnificent examples of the lamp worker's art in its highest form. Should you visit Boston, spend another two or three hours and go to Cambridge to see these glass flowers created by Leopold and Rudolph Blaschka from 1887 to 1895, and by Rudolph alone until 1936.

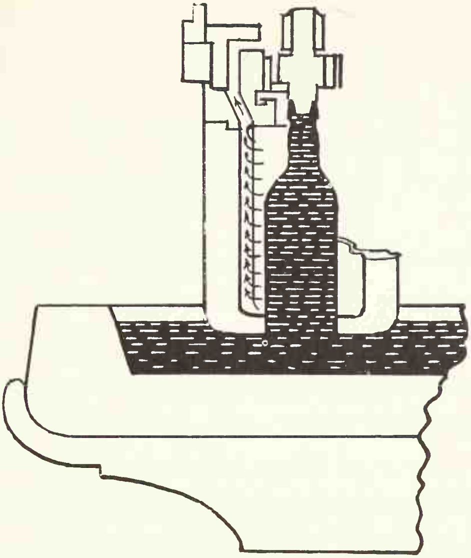
The lamp worker's materials are mostly small sizes of rods, or "canes," as they are sometimes called, and small sizes of tubing. His "lamp" is a gas flame fed with oxygen, and his tools are the simplest kinds of metal pincers and scissors, and shaping tools made of steel or wood. One or two experiments that you can do yourself will illustrate the techniques. They are descibed in Chapter 13.

# 10. Mechanical Lungs and Muscles

THE SKILLS OF THE HANDWORKING GLASSmakers are fascinating to see. But to watch such work or even to try to do some simple glassblowing yourself makes it very clear that soft drinks, shampoo or mayonnaise would cost much more today if the bottles containing them were still made in the old-fashioned way.

In the last chapter you read that a modern machine can make as many four-ounce bottles in three minutes as one man could make in twelve to fourteen hours of handwork. But this speed didn't develop overnight. Many years ago an expert said that the outstanding requirement in designing glassworking machinery is that every operation has to be completed in the short time during which glass is very hot and syruplike. For only a few seconds later, it becomes a hard, unworkable solid.

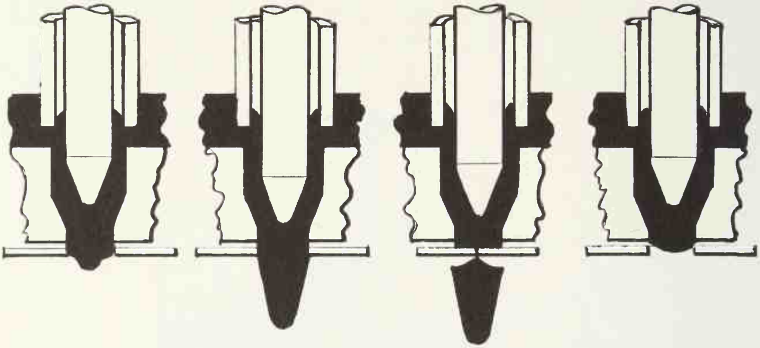
While the handwork artisan can make a leisurely gather on the end of a blowpipe and the bubble can be



Mold was filled with molten glass by suction in the Owens machine.

reheated as often as necessary, the machine must pick up the right amount of molten glass at the right temperature and within seconds complete the forming and solidifying operations at precisely the right time.

To do this, Michael Owens in 1899 contributed one of the most valuable inventions ever made to the machine age of glass. He devised a machine by which the mold for a bottle to be blown was held at the neck and automatically lowered into a tank of molten glass. A vacuum then pulled the molten glass up through the bottom of the mold until it was full. The gather was cut off by shears and compressed air started to blow a bubble. Then, while the bubble was still small, it was transferred to a point where two halves of a bottle mold closed



Mechanical feeder measures gob, pushes it out, cuts it off with shears, and plunger returns for next gob.

around it. As more air was blown, the viscous glass was pushed against the sides, bottom and collar of the mold. When the glass had slightly cooled, the mold opened and released the completely formed bottle to be sent to the annealing oven.

Another feeding method drops a gob of exactly the right shape, size, weight and temperature into a mold. The mechanics of this process are much as though you had a plunger inside a tube like a hypodermic syringe. Push the plunger and a certain amount of glass will be pushed out of the tube. But the end of the plunger is cone-shaped, and when it fits into the mouth of the tube, it acts like a valve, blocking any further flow. Then it returns for another gob. One additional device is necessary for such viscous stuff as hot glass: shears to cut the gob from the mouth, letting the gob drop into the mold that is to do the forming. The mold can be designed for either pressing or blowing.

Pressed glass was first made in quantity in the 1800's when simple, hand-powered machines were used, with a man pulling a lever to force the molten glass into the mold by the pressure of a plunger. Sometimes two or even three men pulled on a lever together when the pieces were large or when the condition of the glass made more pressure necessary.

The same principles are still used, although machines have become automatic and far more sophisticated since the days when pressing first came into use.

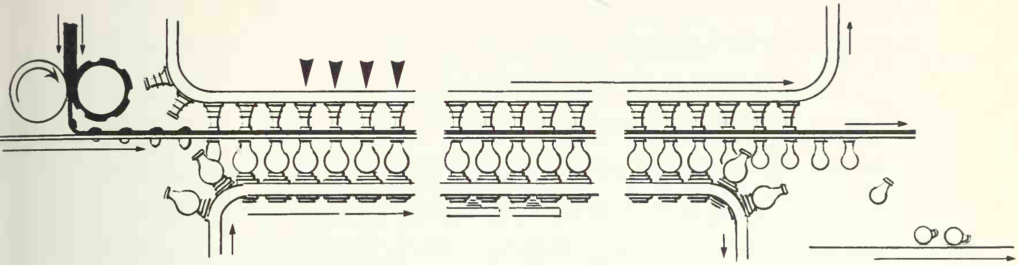
In place of a single-mold machine, many molds are mounted on the rotating table of today's pressing machine. A gob of hot glass is automatically fed to each mold as it comes into position; the powerful plunger squeezes the molten glass into every part of the mold and withdraws automatically. The formed glass stays in the mold and is cooled by streams of air as the table turns. Then, when it arrives at the proper station, the formed glass is automatically ejected and placed on a belt conveyor that takes it through the annealing oven. This kind of pressing machine, with its feed from a continuous tank furnace, efficiently produces ovenware, tableware, lenses and reflectors for automobile headlights, insulators, glass building blocks and many other products. What a difference from one, two or three men pulling with all their weight on a huge lever to force the glass into a mold!

Mechanical lungs, like mechanical muscles, are major improvements, too. While Michael Owens' bottle machine was a vast improvement on hand blowing, the developments since his time have been tremendous. Today machines blow bottles, laboratory beakers and jars, flasks, Christmas ornaments, coffee makers and all kinds of glass enclosures for incandescent-lamp bulbs, radio and television tubes.

There is a machine that makes large glass pieces in two main operations: the neck of a large bottle, for example, is first formed in one mold; then it is carried on to a second mold where the rest of the bottle is made and finished. The neck, by the way, can be formed either by pressing or by blowing, depending on which is the more advantageous for the shape to be made. The body of the container, however, is always finished by blowing.

As you can see from the way these machines operate, the designers patterned them on the general steps that the handworking artisans used for many centuries. But the most remarkable glassblowing machine of all has a completely different approach. This it the Corning ribbon machine that can produce up to 2,000 lamp bulbs or bottles a minute! It is one of the fastest-producing machines in the world, popping out its wares faster than most machine guns can shoot bullets.

The ribbon machine is fed a continuous stream of molten glass from a continuous melting tank. The stream is about one inch in diameter, and is fed to two water-cooled rollers. One roller is somewhat like a pulley, while the other has regular depressions in it, so that as the glass passes between the two rollers, "biscuits" of molten glass are formed on top of a flat glass ribbon. This ribbon is then run onto a moving steel belt in such a way that each biscuit is accurately positioned over a hole in the belt itself. The hole is slightly smaller than



The "ribbon" machine. Note the "biscuits" of glass being fed from the left.

the biscuit. As the belt moves, each molten biscuit sags through the hole and begins to form a bubble that is roughly the shape that it will eventually take—a lamp bulb, a Christmas ornament, or whatever the product is to be. As these hollow gobs elongate, molds, moving below them at the same rate of speed, close around them. They are iron molds with a water-moistened charcoal lining. While puffs of air are then blown into the gobs, the molds spin about them so that a completely even atmosphere of steam envelops the bubble as it is formed. The steam is produced, of course, by the hot glass touching the wet charcoal on the inner face of the mold. Stronger puffs of air complete the forming.

The molds part and fall away, leaving the hot but solidified bulbs hanging from the steel belt where they were shaped. Just before the end of the loop where the belt turns to go back to the ribbon feeder, a small hammer strikes the belt near the point where the bulb is attached. The chilled area near the steel belt makes it break off easily, and the bulb falls onto another conveyor that takes it through the annealing oven and on to human inspectors. Eventually it will take other steps in the manufacture of incandescent lamps or other products.

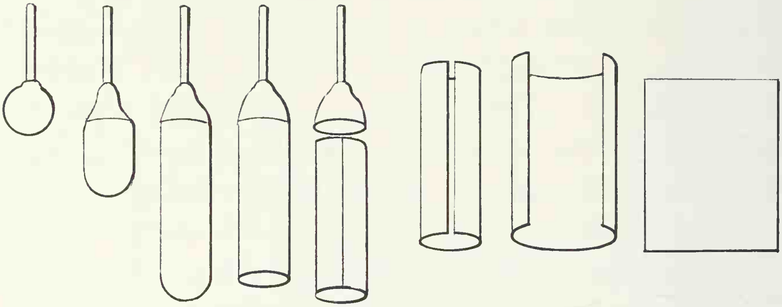
In the days when all glass tubing had to be made by hand, inside and outside diameters and wall thickness were all a matter of skill, guesswork and luck. The method was this: a gob on the end of the blowpipe was shaped by marvering, and the workman started a bubble with a puff on his blowpipe. Then a helper attached a punty iron to the end away from the blowpipe. While continuing to puff into the bubble at intervals, the gaffer walked backward, away from his helper, drawing out his bubble into a very long, thin tube that sagged to the floor where it cooled in a fairly straight line. Sometimes the tube would be as much as 100 feet long! As it was drawn out, a second helper watching the progress of the tube would fan it to cool it in places where he felt it was growing too thin, thus making the glass tougher and resistant to further stretching. Special tubing of unusual kinds that are ordered in very small quantities are made this way even today, for setting up an automatic production machine for very small quantities of tubing would make the cost far higher than the hand-made product.

The automatic tube-drawing operation, of course, works much faster. It produces tubing at the rate of forty miles of it every hour! Molten glass from a continuous melting tank flows through a hole of the proper diameter that contains a mandrel, or ceramic pin, centered in the hole. A toothpaste analogy helps visualize the way it works. It is as though you had a round steel pin centered in the mouth of a toothpaste tube and held from within the tube. Press out the paste, and instead of a solid cylinder issuing from the mouth, the cylinder will have a hole in the center. In other words, the paste will come out in the form of a tube. The pin or mandrel's diameter determines the inside diameter of the tubing, while the diameter of the hole extruding the paste determines the outside diameter. The difference between the two, of course, controls the thickness of the tube's wall.

In the tube machine, as the molten glass flows from the tank, air blowing through a hole in the center of the ceramic mandrel helps to keep the glass a true cylindrical tube. The tube is pulled along a rapidly moving conveyor belt, and the speed of the drawing, the amount of the air pressure and the temperature of the glass, all accurately controlled, determine the final dimensions. At the end of its journey along the conveyor belt, the tubing is cut to convenient lengths. Rods of glass are made in the same way. Drawing a solid rod eliminates both the mandrel and the blowing operation, of course.

Other forms of glass made by drawing are sheet window glass, extremely thin ribbon glass and some kinds of fiber glass.

The old ways of making window glass by hand were two. First there was the crown method, by which a punty was attached to a spherical bubble diametrically opposite the end of the blowpipe. The bubble was detached from the blowpipe and then spun into a flat sheet by centrifugal force. Second was the method of blowing a bubble, elongating it by swinging the pipe held in a vertical position with the bubble down so as to form a cylinder.



The split cylinder method of making window glass.

Then, when the cylinder was formed, it was split parallel to its sides and flattened out into a sheet on a table. In both of these methods, window glass always had waves in it that invariably distorted vision, and no inventions adapting these methods ever overcame that fault.

In 1903 a quantity production method was introduced copying the old handmade cylinder method. According to this innovation, an iron "bait" attached to the end of a blowpipe was lowered into a tank of molten glass. Then, by withdrawing the blowpipe slowly with a power hoist and using compressed air to blow, a cylinder was made that was about forty feet high and thirty inches in diameter. It was then split lengthwise and flattened in the same way as the old-fashioned offhand-blown cylinders had been for centuries. Because the glass could be made faster, it was cheaper. But it still did not solve the problem of waves that were the result of stretching one surface and compressing the other surface of the glass when it was flattened; nor did this method ever succeed in producing a cylinder with completely equal wall thickness throughout.

It was not until 1917 that the first continuous method of making sheet glass was started in the United States. The Colburn machine here, and a similar machine in Belgium, were invented almost at the same time. Also, the Pittsburgh Plate Glass Company developed another machine a few years later. What they all have in common is that they take glass from a continuous melting furnace, pull it through or over rollers, and in one continuous operation they form it, anneal it and cut it from the long strip that starts at the tank and ends with the cutters. This goes on twenty-four hours a day. From the time the materials arrive at the "batch house" where they are mixed, through the melting and fining operations of the tank and the time the glass arrives at the cutters, not eighteen hours have elapsed!

Plate glass differs slightly from ordinary window glass in its composition, although they are both soda-lime-silica mixtures. But the great difference is that plate glass is essentially an optically superior product. It was not until about 1923 that plate glass was ever made by a continuous process. Up to that time all plate glass was made by a refinement of the methods used long before in making sheet glass: casting molten glass on a flat table.

In modern times, power hoists lifted large pots of molten glass, poured them onto iron tables covered with fine sand to prevent the glass from sticking to the iron, and immediately following the pouring, a heavy water-cooled roller ironed it flat, just as a piecrust is rolled out with a rolling pin. After annealing, the rough glass was fitted into a bed of plaster of Paris, on a table twenty-five to thirty feet in diameter, that was then put into a grinding and polishing complex that started grinding the rough glass with coarse sand and water. This was followed by finer grades of sand, then emery and water, and finally polished with water and rouge (iron oxide) applied with felt-covered wheels. Thousands of tons of sand, glass and iron particles accumulated around every factory engaged in this process, to say nothing of the tons of plaster of Paris that added to these man-made mountains. About half of the thickness of the original glass was ground away before the process was completed!

The continuous process, which has now largely supplanted the above method, takes molten glass that flows from the refining end of a continuous melting furnace and passes it through water-cooled rollers as a ribbon of uniform thickness and width, through the annealing process and through grinding and polishing machines that operate on both surfaces of the glass as it moves. The ribbon of glass, up to 11 feet wide, stretches from forming rolls to cutters in a single piece that is 900 feet long!

The newest method of all is one that completely eliminates grinding. It is the British Pilkington Brothers' process, in which the ribbon of glass goes from the forming rolls to a long trough of molten tin where it is floated throughout its journey. In the course of its trip its lower surface becomes completely leveled by floating on the molten tin, and, passing under a battery of flames in an atmosphere of inert gas (to decrease oxidation of the tin), the upper surface is fire-polished. It is said that this glass is as good as or perhaps better than conventional plate glass because it does not have the very minute surface scratches that are present in ground and polished glass.

It has been said of all mechanically polished surfaces that the highest polish is the one with the smallest scratches. (This is why you use finer and finer grades of sandpaper on wood, and finer and finer grades of steel wool on shellacked and varnished surfaces, and so on to wax and cheesecloth.) Fire-polishing of glass presumably eliminates most surface irregularities, and certainly flames do not scratch! More and more plants are being converted to this "float-glass" method of production. It is reported that the president of a rival glass company said to an associate at the opening of a new forty-million-dollar plant of the old grind-and-polish design built after the Pilkington method was proved successful, "You are now looking at one of the most modern obsolete plants in the world."

It is claimed that the float-glass method may cut the cost of plate glass as much as 25 percent, in spite of the rate Pilkington charges for licensing the use of the process by other companies. The Pilkington Company spent a great deal of money in developing their method, and had to scrap more than 100,000 tons of glass before success finally crowned their experiments.

The first glass made by this process had to be about one-quarter inch thick, because at that thickness it floated exactly the right way on the surface of the molten tin. But improvements have been made so that both thicker and thinner plate glass can be made by this newest and most economical method.

The safety glass in your automobile is plate glass that has been laminated with a plastic filling between two layers of glass. Heat and pressure cement the three pieces together so that when anything breaks the glass it will still be held in position—cracked in a thousand pieces, perhaps, but not splintered the way ordinary glass is when broken. The invention of this life-saving feature for automobiles was, like so many inventions, the result of careful observation by a man who was both informed and curious enough to follow up what he observed.

He was a Frenchman named Edouard Benedictus. One day in 1903 he dropped a glass jar on the laboratory floor. When he picked it up he found that it was badly cracked all over. But amazingly, its pieces were firmly held in position, almost as if the jar were still whole. What *could* have caused this?

Benedictus studied the jar carefully. The label showed that he had put it there years before and that the jar's contents had been a mixture that included celluloid. The liquids had evaporated, leaving a film all over the jar's interior. But the scientist could see through the jar. It was still transparent and the dried-up coating inside was not visible.

Such a material might have some use. But just then Benedictus' time was completely taken up with research in a different field. He pasted another label on the jar, telling what had just happened to it and set it away to examine when he had the chance.

A number of years later he read of an accident to a woman riding in a horse-drawn cab. She was badly cut when the animal was frightened and shied, and she was thrown against a window broken during the excitement.

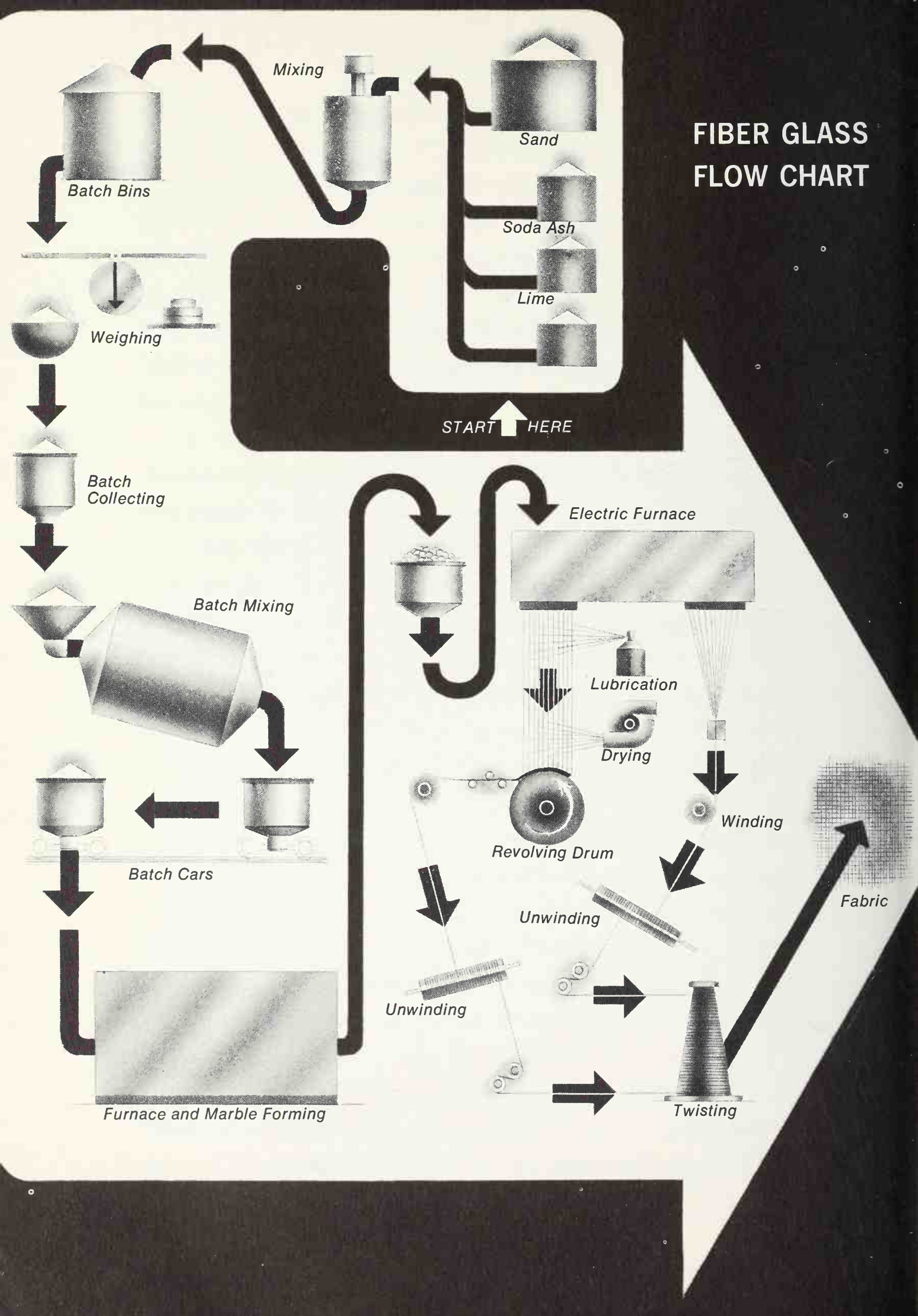
Benedictus suddenly remembered the glass jar that had cracked but had not shattered. Possibly he could make safe glass for vehicles and prevent many such accidents.

He set to work at once, trying first one experiment, then another. At first he could not make a shatterproof glass that was strong enough. But at last he held the first piece of safetyglass in his hands: two pieces of glass securely stuck together with celluloid!

Another plastic was substituted later, since celluloid yellowed and blistered. Today windshields and windows on every car are made of safety glass.

When you happen to notice window curtains, you are apt to guess they are cotton, linen or rayon. But more and more glass fabrics are being used because of their obvious advantages: they are fire-resistant, rainproof, colorfast, collect very little dust or dirt, and wash and drip-dry speedily, require no ironing and are an absolute minimum of trouble wherever they are used. Glass fabrics start exactly like every other piece of glass—with sand and the oxides in a furnace. But the first product in one method is not the glass fiber for the fabric. It is a huge quantity of glass marbles about half an inch in diameter. It is made in this form for easy inspection, and any with

## FIBER GLASS FLOW CHART


Mixing
Sand
Batch Bins
Soda Ash
Lime
Weighing
START HERE
Batch Collecting
Electric Furnace
Batch Mixing
Lubrication
Drying
Winding
Revolving Drum
Fabric
Batch Cars
Unwinding
Unwinding
Furnace and Marble Forming
Twisting

impurities are thrown out. Then they must again be melted, and this glass has to flow through tiny holes less than twenty-five thousandths of an inch in diameter. This diameter is so fine that each marble will produce ninety-three *miles* of fiber! There must be no impurity in the glass that would block the holes of the "spinneret" that produces the fiber.

The glass-fiber spinneret is adapted from the one that was invented for the production of "artificial silk," as the first rayon was called. A little like the head of your shower, it is made of a very special metal alloy and has hundreds of holes in it.

When the molten glass flows through the spinneret, the many fibers coming out of the holes travel to high-speed winders that run at 120 miles an hour. Twisting the fibers and bonding them together to make handling easier in standard textile machinery is the next step.

Once the glass fibers are woven, the fabric gets a heat treatment that sets the weave so that it never has to be ironed. The temperature of the heat treatment is 1200° F. No natural fiber and no other man-made fiber can stand this kind of heat, so glass fibers cannot be combined with them.

After setting, a protective coating of resin and pigment color is applied. Dyes used in ordinary fabrics are liquids. But since glass will not absorb liquids at all, another method of coloring had to be developed for fiber glass. Special pigment dyes and resins are bonded to the glass in curing ovens. Then one further treatment ensures the washability of the finished fabric. Pigments, resins and glass are all thoroughly washable and sun-fast. But don't ever send fiber-glass curtains to a dry cleaner, for sooner or later dry-cleaning solvents will break down the color.

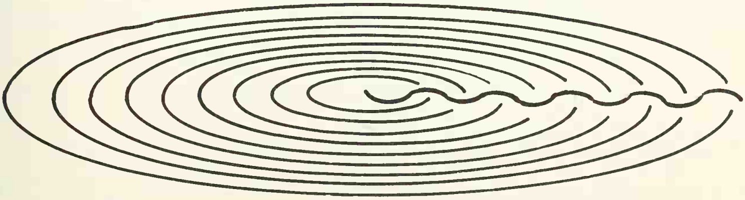
The glass-fiber industry started in the 1930's. The first products marketed were air filters that caught all but the very finest airborne particles when drawn through a tangled network of minute fibers that were coated with an adhesive material.

Fiber for filters, as well as fiber later developed for insulation, differs from the continuous fiber for woven fabrics in that it is formed with high-pressure steam or air. When the fibers are pushed through the holes of the spinneret, they are blown by the high-pressure jet upward into a chamber, coated with an adhesive material at the same time, and then allowed to fall, helter-skelter like elongated snowflakes, where the fibers are collected and formed into long rolls, or formed into "bats" of the required widths and thickness. The adhesive holds the fibers together in the random pattern in which they fall. This material is used to insulate houses, refrigerators, ovens, water heaters, aircraft and has a great variety of other applications where heating or cooling processes are involved.

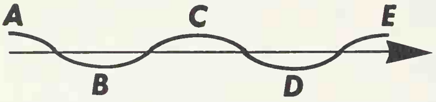
# 11. Why Is Glass Transparent?

SCIENTISTS SAY THEY CANNOT COMPLETLY explain the transparency of glass without going deeply into mathematics. But the electromagnetic theory of light, they tell us, is the basis for any explanation.

Light, this theory holds, is a form of energy that is a vibrating electromagnetic force. Like radio and television, light moves in space in waves. Throw a stone into a pool of water and it will start a series of waves, traveling outward in larger and larger circles from the center, while each particle of water in each wave moves up and down. Notice that a cork floating on the water a slight distance

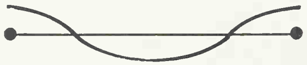


from the center will move up and down, but it does not move away from the center. Electromagnetic waves of light move away from a light source in much the same way. If we consider just one ray of light, its direction of travel would be a straight line, while the wave vibrations are up and down, something like this:

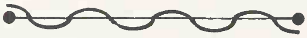


Various colors of light differ in their wavelengths, which are measured from the crest of one wave to the crest of the next: from A to C or from B to D, or from C to E, etc. Red light has the longest wavelength of visible light; violet has the shortest. Since all light (all electromagnetic waves, too) travel at the same speed in air, those with the longest wavelengths have the slowest rate of vibration. You can see that if it takes both red and violet light the same length of time to go the distance be-

tween these two points, the one with the long wavelength:



will vibrate fewer times than the one with the short wavelength:

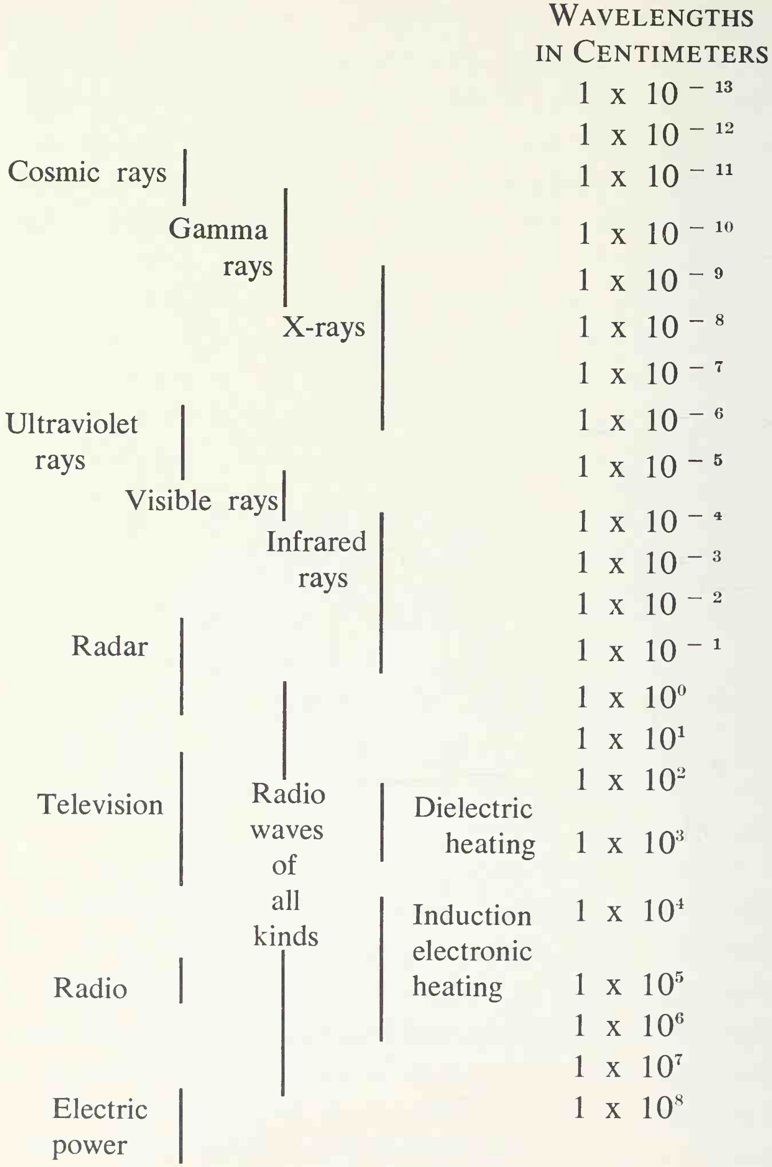


(The illustration exaggerates the difference between the shortest and longest wavelengths of visible light. The shortest visible violet wavelengths are about 400 millimicrons, abbreviated mμ; the longest visible red wavelengths are about 750 mμ. It takes about 25,400,000 mμ's to cover an inch.)

All the following forms of electromagnetic energy move at the speed of light. Here is a list arranged in order, from the shortest to the longest wavelengths. Cosmic rays, gamma rays, X-rays, ultraviolet rays, visible rays, infrared rays (heat), radar, television, radio waves and electric power waves. As you can see in the chart, on page 136, the wavelengths of some of these rays overlap, while some begin at the point where others end.

It is easy to think of X-rays or radio waves passing through solid objects, for we have seen the evidence of it many times. Perhaps you have seen X-rays of your own teeth; perhaps you have seen X-ray pictures shown in movies or television shows. Yet there are some things X-rays can't penetrate, such as thick lead shields that stop them cold. And when an automobile radio goes underneath a steel bridge you have proof that radio waves can be stopped, too!

To understand why some waves pass through some solids and not others, we must know something more about the atom. In the chapter on chemistry, you read something about it. Perhaps you already know that the atom is composed of a nucleus that is accompanied by from one to ninety-two electrons in constant orbit around the nucleus. The hydrogen atom has one electron, the helium atom has two electrons that orbit about its nucleus, and so on, up to the heaviest element in nature, uranium, with ninety-two electrons.


WAVELENGTHS IN CENTIMETERS
1 x 10 − 13
1 x 10 − 12
Cosmic rays
1 x 10 − 11
Gamma rays
1 x 10 − 10
1 x 10 − 9
X-rays
1 x 10 − 8
1 x 10 − 7
Ultraviolet rays
1 x 10 − 6
1 x 10 − 5
Visible rays
1 x 10 − 4
Infrared rays
1 x 10 − 3
1 x 10 − 2
Radar
1 x 10 − 1
1 x 10⁰
1 x 10¹
1 x 10²
Television
Radio waves of all kinds
Dielectric heating
1 x 10³
Induction electronic heating
1 x 10⁴
Radio
1 x 10⁵
1 x 10⁶
1 x 10⁷
1 x 10⁸
Electric power

Note: $10^0$ is 1; $10^{-1}$ is .1; $10^{-2}$ is .01, etc.
$10^1$ is 10; $10^2$ is 100; $10^3$ is 1,000, etc.

Metals do not transmit light, as everyone knows. In metals, the scientist explains, some of the electrons are quite free to migrate from their usual orbits, and when light strikes these "free" electrons, they interact with and influence the electrical and magnetic characteristics of these waves called light. They change the electromagnetic nature so drastically that what remains thereafter is not light at all. Its energy is wholly absorbed.

In glass, on the other hand, there are no free electrons. Because the electrons in glass cannot move freely as they do in metals, they do *not* interact with the light wave, do *not* change in character, so that they permit the light wave to pass through the glass with most of its strength intact.

Light waves pass through gases and air easily because normally there are *too few* atoms and electrons present in gases and air to interact with the electromagnetic waves of light. To illustrate the difference between a solid and a gas with respect to this concentration of atoms and electrons, consider the carbon dioxide you know in soft drinks. You can't see the gas when it fizzes; you see only its effect. But when carbon dioxide is compressed and the temperature is brought down to make dry ice, it is no longer a gas. The number of atoms and electrons compressed into a small space is so great that it becomes a solid and with respect to light it *behaves* like a normal solid: you cannot see through it, for as in metals, there are enough free electrons to interact with light waves and absorb their energy.

Good plate glass will transmit about 92 percent of the light received. We can see the glass, however, because we see its surface—actually, because we see the light that its surface reflects. To maintain transparency in glass, there must be a minimum of light-scattering particles of non-glassy substances within the glass, and a surface with a minimum of scratches. You can see the effect of foreign particles in some old glassware and in some old window glass. It is foggy at best, and practically opaque at its worst. As far as surface scratches are concerned, you need only look at a pair of roughly treated eyeglasses to see what happens when glass is scratched.

The extreme result of surface roughening or scratching may be seen in glass that has been deliberately etched, like the inside of lamp bulbs, or sand-blasted, like the glass sometimes used in office partitions or in bathroom windows. They permit transmission of some light without complete transparency. Take such frosted glass and cover its surface with oil and you will find that it becomes far more transparent, because the rough surfaces are smoother, in effect, and no longer reflect light or scatter it to nearly the same extent.

An even more dramatic demonstration can be seen if you immerse a glass article in monochlorobenzene. This long-named chemical is as clear as pure water, but you cannot see the glass article beneath its surface. That is because the optical characteristics of both glass and liquid are the same, so that it is as though you had one solid piece of glass, or a jar full of liquid and nothing else. The same thing is true of ground glass. In air, ground glass is a white powder, even though each particle is in itself transparent, as you can see under a microscope. But pour it into a dish of monochlorobenzene and it becomes invisible! To have this effect, it must be stressed that both the glass and the chemical must have the same index of refraction.

What is the index of refraction? Well, let us see.

When you look at a long, straight stick that you have put into a pond of water at an oblique angle, you will see that the stick seems to bend at the surface line. If you have your diving goggles on you can look up at the stick from below water and see that it seems to bend in the opposite direction when you see it in air. This is the optical phenomenon known as refraction, and the index of refraction is a measure of the degree to which a transparent material bends light.

What occurs, actually, is that when light enters one transparent material such as water, from another, such as air, at an oblique angle the light's speed is slowed. The index of refraction is the ratio of the speed of light in air to the speed in any other transparent material being measured.

What happens when you place a glass article in a liquid with the same index of refraction? Normally, you see only the surfaces of the glass article. But the liquid has the same capacity for bending light as the glass has, and since there is no change in the direction of the light as it passes from the liquid to the glass or from the glass to the liquid, there is no change of light that the eye can detect. So the glass is invisible. Also, if you could make glass with the capacity to transmit light at the same speed as light in air, there would be no surface you could see! Perhaps it is just as well that glass of that kind can't be made. Just imagine all the bumps and broken noses that would result from bumping into doors made of glass like that!

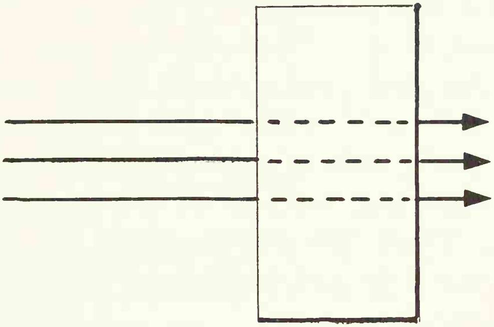
The measurement of the index of refraction is of major importance to optical instruments of every kind. The speed of light in air has been measured in countless experiments by many methods, and it is generally accepted to be 186,000 miles per second. The speed of light in water has been determined as 140,000 miles per second. So the index of refraction for water, which is the ratio between these two speeds, is $\frac{186{,}000}{140{,}000} = 1.33$.

For a particular kind of flint glass (made with lead oxide) in which light travels at 113,000 miles per second, the index is $\frac{186{,}000}{113{,}000} = 1.65$.

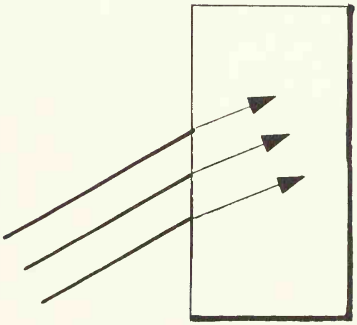
A crown glass, made with silica, potassium, sodium and barium oxides in which light travels at 122,000 miles per second, has an index of refraction $\frac{186{,}000}{122{,}000} = 1.52$.

The practical effect of this phenomenon can be seen like this: If a beam of sunlight (the rays of which are always practically parallel) strikes a piece of flat glass with parallel surfaces at right angles to the surface, all the parallel rays arrive at the surface at the same time.

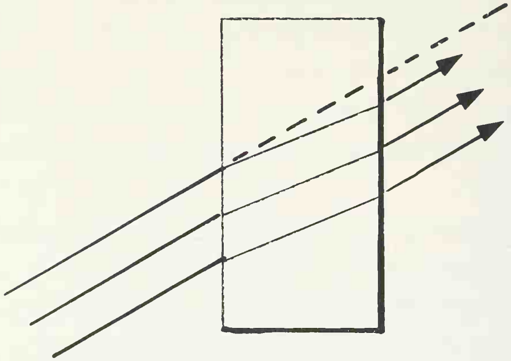
They will be slowed down as they pass through the glass. But all rays will travel at the same slower speed than through the air.



If a beam of sunlight strikes the glass at an angle, however, the beam is refracted, or turned from its original path:

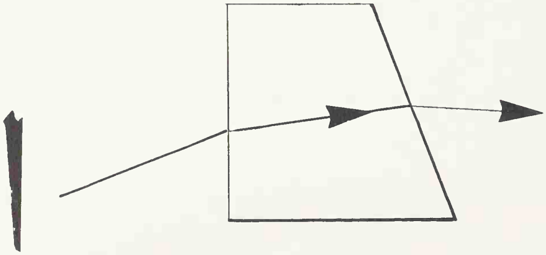


When the light passes from the glass to air, there is another change in direction: the light returns to a path parallel to its original direction, but displaced sideways.



The dotted line shows where the top ray would be, had the glass not been there to bend it.

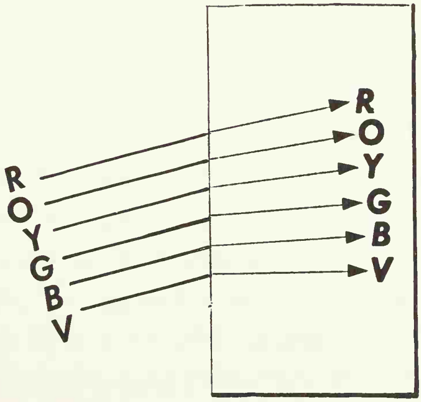
As you can see from the above illustrations, the two sides of our plate glass are parallel. But if the two sides are not parallel, a ray of light will not continue in its original direction when passing out of the glass into air again, but in a direction that is controlled by the original angle between the light and the first surface (angle of incidence) by the index of refraction, and by the angle between the two surfaces of the glass.



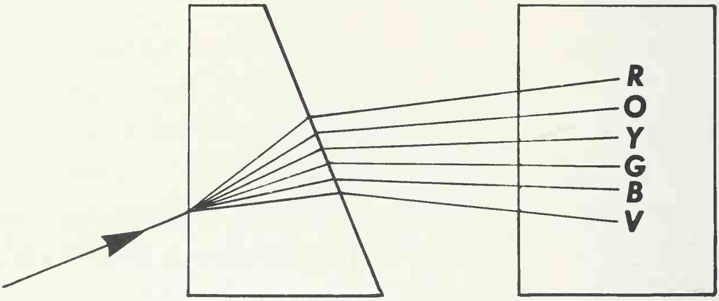
White light is actually composed of red, orange, yellow, green, blue and violet. (Want to remember it in that order? Then memorize the made-up name, "Roy G.

B. Violet," using the initial letters of the first five, and the name of the color with the shortest wavelength.) A color wheel proportionately composed of these colors and rotated on the shaft of an electric motor at high speed appears to be white. The reverse is evident when sunlight strikes a pendant of a chandelier, or a cut-glass dish: The white light is separated into its component colors, and you get a rainbow color effect.

As has been said, all light travels at the same speed in air. But when a beam of white light enters a piece of glass, the various wavelengths are slowed down according to the color: red travels fastest in glass, orange slower than red, and so on. The refraction, or bending of light, of those colors runs from least to most, in that same order, as this diagram illustrates.



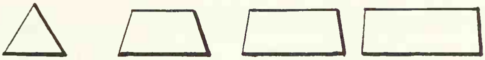
If one could isolate just a single ray of light, when the various wavelengths emerged from the other side of the glass they would be separated so that you could see their colors. But this can't be done because one ray is so small. The way that we *can* see it is by passing white light through glass that does not have parallel sides. This is what happens:



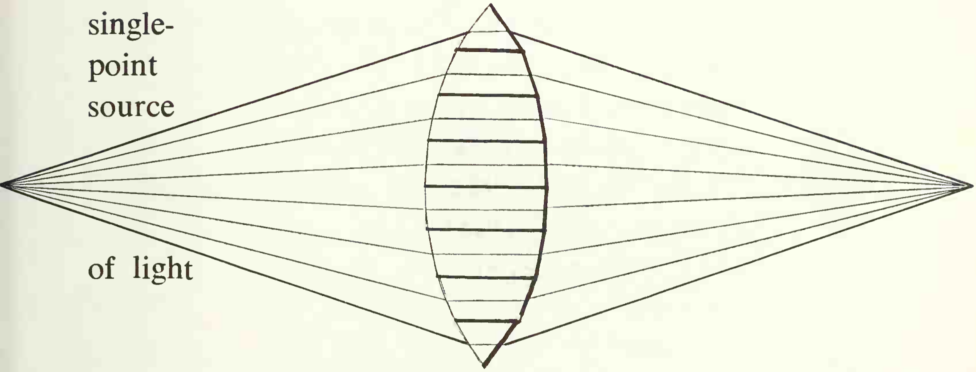
The spectrum of colors has been formed not only inside the glass, but outside, because each color emerges from the glass in a direction that is different from the incident ray of light. If you set up a screen to view the colors, the farther away from the emergent side of the glass, the greater the separation there is between the various colors.

This phenomenon is know as dispersion. While a rainbow of this kind is pretty to look at, it would be a serious fault in fine optical instruments. Before men learned to correct their instruments for such a fault, microscope images always were fringed with a kind of rainbow halo that made a really sharp-image focus impossible. More about this later.

What is a lens and how does it work? To illustrate, suppose that you have a number of pieces of the same kind of glass (with the same index of refraction) in the following shapes.



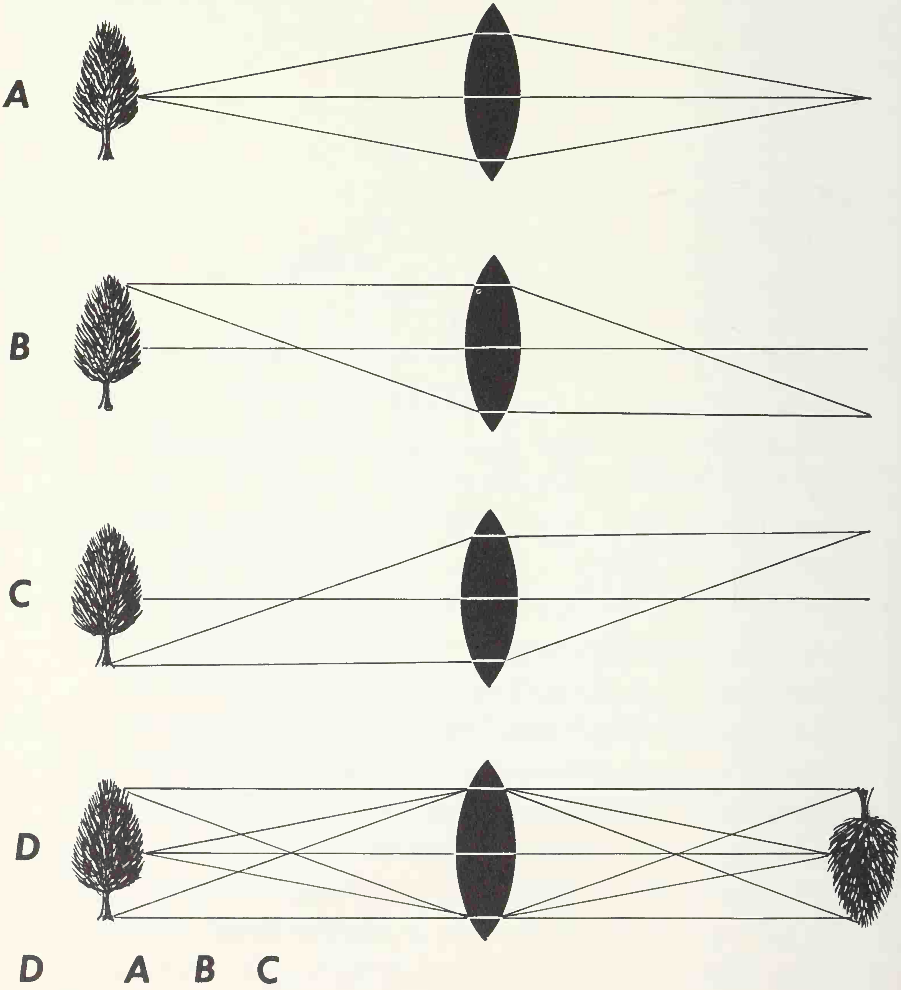
Now, pile them up and turn a duplicate set upside down so that you end up with this:



Assume now that instead of eight pieces of glass, this is one piece, and that instead of having straight sides, each side of the glass is formed like a section of a sphere. It should be apparent from this how a lens of this kind can take light from a source and, by refracting the many rays, converge the light to a focus on the other side.

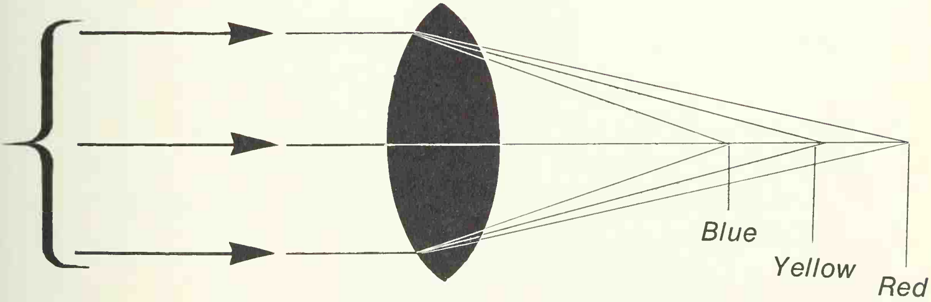
By changing the curvatures of one side or both sides of the lens, or by using glass with a different index of refraction, the point at which the converging rays will come to a focus can be changed to meet the requirements.

In the illustration above, the source of light is indicated as a single point. The image, then, would be a single point, too. Then how does a lens work in projecting an image from thousands of points? These illustrations will help to explain.

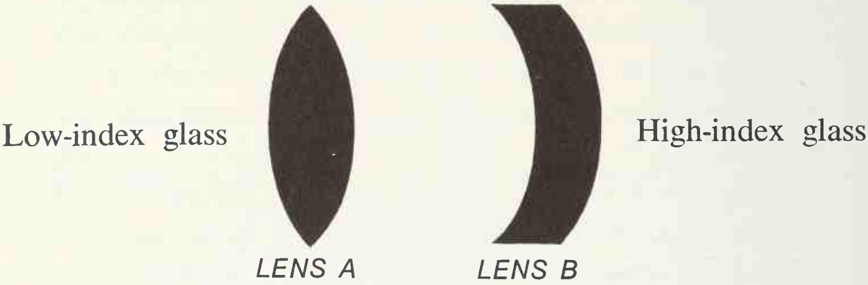


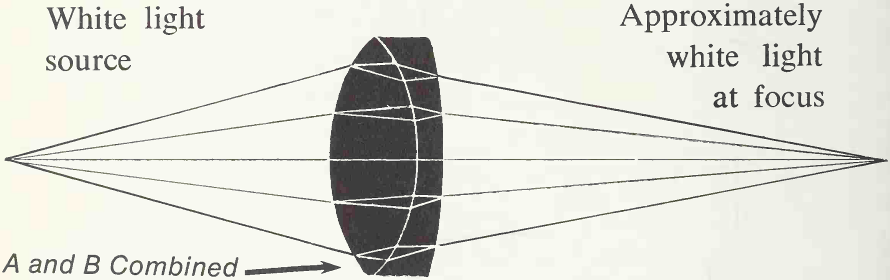
The light from the center of the object in A is on the optical axis of the lens, and will be brought to focus on the optical axis on the other side of the lens. In B, the light from the top of the object will be brought to focus at the bottom of the image. In C, the reverse is true. And every other source of light from the object will be brought to focus in the same manner at the image points somewhere between.

We pointed out earlier that light of different wavelengths—different colors—travel at the same speed in air, but are slowed to different speeds in glass. The fringe of color that edged the images of early microscopes was the result of this. It is known as chromatic aberration, and it results from the focusing of these different wavelengths at different distances from the lens.



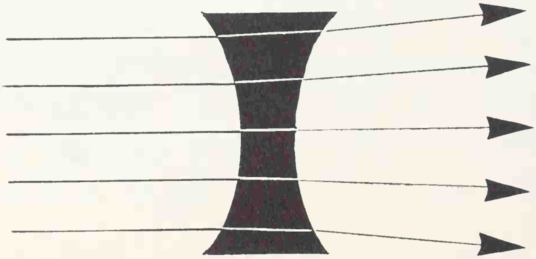
To avoid the difficulty, a special light can be used that is almost entirely one color, such as a sodium vapor light. Or a color filter can be used that cuts out nearly all colors but one. Then there is a combination of two lenses made of two kinds of glass. One has a low index of refraction, the other a high index of refraction. Combined, they compensate (counteract each other), and the combination is known as an achromatic lens. It looks like this:


Low-index glass
LENS A
LENS B
High-index glass


White light source
Approximately white light at focus
A and B Combined

The double convex lens converges light and brings it to a focus on the opposite side from the object, as the illustrations above have shown.

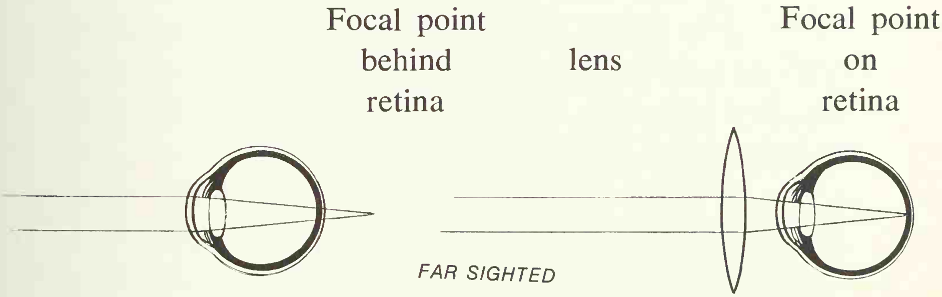
The double concave lens takes light in and diverges it like this:



One of the most important uses of glass, as we know, is the correction of faulty vision.

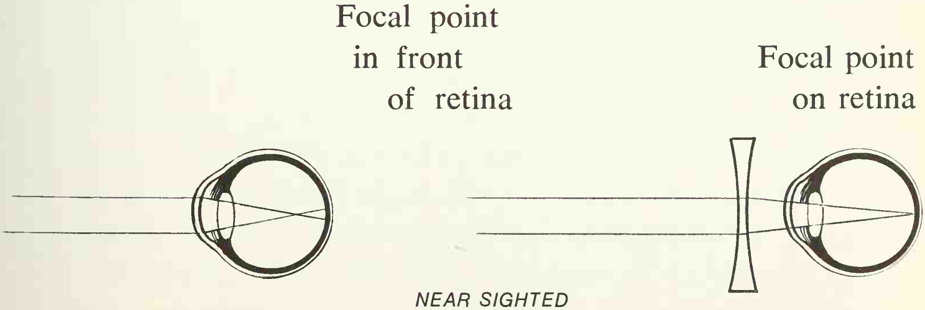
There are many kinds of corrections that have to be made. We will illustrate two of the simplest solutions.

In the far-sighted eye, the focal point of the eye lies back of the retina instead of right on the retina as in the normal eye. See the illustration of the far-sighted eye on the left, below. The lens used to correct this is a double convex lens that converges the rays so that the image is received on the retina in precisely the right place, as shown on the right.


Focal point behind retina
lens
Focal point on retina

FAR SIGHTED

In the near-sighted eye, the reverse is true, and the double concave lens is used to compensate. The two conditions are shown left and right below.


Focal point in front of retina
Focal point on retina

NEAR SIGHTED

# 12. Modern Glass

After the invention of the blowpipe, glassworkers evidently became so fascinated with the new fields that it opened to them that for hundreds of years they devoted nearly all their efforts to making new objects of art. They made them in the most elaborate forms and colors. But their efforts to change glass composition or characteristics seem to have been confined to avoiding impurities that would hamper their artistic efforts.

It wasn't until 1676 that anything new appeared to change the character of either the raw materials of glass or the finished product. But that year an Englishman, George Ravenscroft, introduced a kind of glass that had the greatest brilliance so far achieved. He used lead oxide and a very pure form of silica—flint, which gave its name to the glass. This produced a beautifully clear glass that was softer than previous kinds and easier to work. In addition, it was discovered later on that it had a high index of refraction and great dispersion power. It has proved to be extremely valuable in many optical applications, as well as in the artistic field, for which it became immediately famous.

Ravenscroft's lead oxide was not a completely new ingredient of glass. It was used by the Romans and by the early Venetians, but differently: as a flux to make other ingredients melt more easily and in making red glass. Also, they used it in very limited quantities. But Ravenscroft used a great deal and today very dense optical glass is occasionally made with as much as 79 percent lead oxide to 20 percent of silica. This is a very high proportion, of course.

English glassware flourished as a result of the new, brilliant glass with its ringing tones and its ease of decoration by engraving and cutting. The most important thing about it was that for the first time raw materials had been changed in order to produce more desirable properties in the finished glass.

A whole century went by before anything as revolutionary happened in glassmaking again. This time it was in France, where Pierre Louis Guinand, a Swiss glassmaker, did something that *sounds* very simple: he stirred the pot of glass as it "cooked." But stirring hundreds of pounds of molten glass is not a simple thing to do. Try it with an iron rod: not only will the iron contaminate the glass, but the rod itself will become so soft as to be useless.

It was impossible, before Guinand, to make a good optical lens that was more than three or three and one half inches in diameter, because nobody had found a way to make large pieces of optical glass that didn't have striations in them—long, stringy imperfections that threw the light rays in crazy directions and ruined the images. But in 1790 Guinand produced some lenses that were huge for their time: as much as nine inches in diameter! For years he kept his method secret. Finally it came out: To get a really homogeneous glass, he stirred the molten glass with a rod of fireclay—the same kind of clay that was used to make the pot that held the glass.

In the preceding chapter you read about the difficulty with color fringes around the edges of optical images—chromatic aberrations—and how they were avoided by the use of two kinds of glass. It was the work of Guinand and two Germans whom he joined in Munich that led to a complete search for new constituents in glass.

A systematic search for different kinds of glass began in the early part of the 1800's. The method was to try new ingredients, one after another, and test the result. But until Otto Schott began his work in Germany about 1881, only five or six kinds of glass materials were in general use, except for ingredients added in order to bring about changes in color. Schott and his associates introduced more than twenty-five new materials to glassmaking. They started a trend in the industry that has flourished ever since.

In 1908 the Corning Glass Works established one of the first industrial research departments in the United States with only one chemist, Dr. Eugene C. Sullivan. Hundreds of research men work there today. They have made and recorded the properties of well over 125,000 glassmaking formulas and are still searching for and testing thousands of new combinations every year.

Dr. Sullivan had studied at the University of Michigan and the University of Leipzig. He started the search for a glass that wouldn't break as had the train signalman's hot lantern globe when the cold rain struck it. In 1912 he and William C. Taylor found such a formula, and soon afterward, Corning made lamp globes that cut breakage by 60 percent.

Unsatisfied with this result, they carried on. They came up with Pyrex in 1915. Today this is used in ovenware, laboratory ware, piping, sealed-beam headlamps, and hundreds of other applications where chemical and heat resistance are important. The heat and chemical-resistant glass made under the name of Pyrex is a borosilicate glass. There are many variations of the formula for special uses. Want a tan? It might be expensive, but you could install a special-formula borosilicate window on the south side of your house: it transmits the ultraviolet light that tans (and sometimes burns).

Following Ravenscroft's introduction of lead glass about 1676, many thousands of pieces of fine lead-glass tableware were made. Because it can be easily worked and offers such unusual sparkle and luster, it is this type of glass that is used to make fine "crystal," such as the famous Steuben art glass made at the Corning Works in Corning, New York. Because lead glass has an unusually high capacity for transmitting infrared (heat) rays, in addition to its use as an art glass it is used in heat-seeking missiles. Lead glass is not ordinarily made in panels or window-glass form. But if you had a window of this kind of glass, you might get very warm sitting behind it in the sun, but you would not get a sunburn, for lead glass blocks the ultraviolet waves that tan. In its heaviest form, lead glass is used for radiation shielding in atomic installations where technicians must be protected from deadly rays. Most glass discolors from gamma rays but this glass stays clear. Combinations of special oil between layers of lead glass have been used to make windows eight feet thick for gamma-ray protection.

Radiation-*sensitive* glass, which *does* discolor from radiation, is used for dosimeters. When it is worn by a worker in atomic plants or atomic submarines or ships, it records the amount of radiation he has received.

Before the First World War, nearly all optical glass and nearly all glass for laboratory equipment was imported by the United States from Germany. Then, when our supply was cut off, American manufacturers were besieged with requests for products they had never even tried to make at all, or at most, in small quantities. Even the clay we had used for the glass melting pots had been imported from Germany. We were in a spot. But not for long, because necessity combined with ingenuity forced our technicians to do things they had never done before. The result was that American glassmakers not only learned to equal or better the quality of optical and other glass products of Germany, but they have gone on to produce things that had never been known anywhere before World War I.

It had been noted in 1920 that some heat-resisting glass lost its resistance to acid after it had been heated for a long time. Nobody paid much attention to this oddity until ten years later, when Harrison Hood at Corning Research was puzzled by this peculiar behavior. Working with Dr. Martin E. Nordberg, he discovered that glass with high percentages of borax could be greatly changed by heat treatment followed by an acid bath. After months of work, they found a way to dissolve the borax from a thin piece of glass. What was left was like a solid glass sponge with millions of holes in it that were so small they couldn't be seen under the most powerful microscope. They put a glass bar of this acid-treated glass in an instrument that would heat it and measure the expansion. When the temperature got up to 600° C., the pointer on the dial wavered and then unbelievably began to move *in the wrong direction*: the glass was shrinking! This was what they had *hoped* might happen, but they couldn't be sure until they made the experiment.

They found that they had dissolved nearly all the borax, and when the cloudy glass was subsequently heated, it shrank more than a third, and became a clear, 96 percent silica glass. A dish of this glass can sit unharmed on a block of ice while it is filled with molten bronze! Acids won't bother it, either, and it will transmit all the rays of light from infrared to ultraviolet.

That intermediate glass with the millions of invisible holes in it was immediately nicknamed "thirsty glass." It absorbed moisture from the air or from any material it touched. It even caught particles of smoke in holes so small that you would have to enlarge them 12,000 times to attain the diameter of a human hair. As a filter, with holes less than a millionth of an inch in diameter, thirsty glass can capture viruses no other filter ever could catch. Such filters are used in producing the Salk vaccine against polio and for other purposes.

Glass scientists have measured temporary tensile strength in fibers up to 2,000,000 pounds per square inch. They believe it is possible that strength may go as high as 3,000,000 pounds per square inch! Although practical strengths today are far below those figures, tempered glass is amazingly strong. Dr. Jesse T. Littleton had pointed out by 1920 that the strength of tempered glass came from strain produced in rapid chilling. This was exactly what happens in Prince Rupert drops: the outside of the glass cools rapidly, leaving the inside with an internal pull or tension that has to be overcome before the glass will break.

Scientists began tempering lamp globes and insulators with considerable success. But when they tried to temper glass for top-of-the-stove use in kitchens, they ran into trouble. They could not equalize the tempering in all parts of complicated shapes because they couldn't chill thick and thin sections of glass to the same temperature at the same time. When things were unequally chilled, breakage was *explosive* when it *did* occur. So they looked for ways of quick, equalized cooling. Water immersion wouldn't do it. Cold-air chambers wouldn't do it. Oil baths left an impossible job of cleaning up charred oil on the glass after it came out of the bath, and the tempering wasn't adequate, anyway. Finally, by using molten chemical salts, they found an answer. In 1936, top-of-the-stove glassware was a success.

Since that time, methods have been developed so that those parts of a piece of glass that are naturally weakest, such as the rim of a drinking glass, are given the benefit of the greatest tempering with cold air; and the tempering is tapered off toward the strongest parts, such as the base of a tumbler. Air tempering has grown in use as the technique was improved, and there is hope that someday tempered glass will be so fantastically strong that it will match or excel any other material.

From the time that Guinand stirred optical glass until World War II, the same methods were constantly used. In a good clay pot the materials were melted and stirred slowly and carefully with a fire-clay stirring rod. When the glass was allowed to solidify, it was chipped out of the pot in chunks and reheated so that it sagged into block-shaped molds. The blocks were inspected and again chipped to take out specks, bubbles and impurities. Finally, from about 2,000 pounds of the original glass, perhaps 200 pounds were used to make fine lenses.

Back in 1920 Dr. Gordon S. Fulcher at Corning had showed that much better control of the quality of glass was possible in electrically heated tanks. When demands for lenses for our armed forces piled high in 1943, Corning scientists began research on optical glass production with a vengeance. They lined melting chambers with costly platinum so they could avoid the impurities that always crept into glass from the clay pots they had been using. They developed several new ways of stirring. Dr. Charles F. DeVoe worked on electric melting and stirring. Dr. John F. G. Hicks invented a machine that poured molten glass from one container to another and back again to blend it.

Even though they seemed to have no hope that they would get them for months, the Army placed an order for 125,000 lens blanks. For weeks after, whenever they asked about progress, the answer was simply, "No lenses yet." Dr. DeVoe's group had made more than twenty-four different electric furnaces. Then they finally built another new design and put it to work. In a few days the Army telephoned their usual question and DeVoe answered, "The order is more than half made. It will be completed in a week."

The new furnace and tank were amazing. They produced up to fifty pounds of optical glass every hour! Since that time even greater improvements have been made; with new blending methods, a whole ton of flawless optical glass can be cast in optical blanks up to three feet in diameter!

Those lavender windows on Beacon Street in Boston and the color in bottles and windows in the desert where they have long been exposed to sunlight got that way from the ultraviolet light of the sun. This fact led Dr. Robert H. Dalton at Corning to believe that ultraviolet irradiation, if added to an old method for making ruby-red glass, might improve its color. He decided to experiment. Mixing gold and copper with a batch of material, melting it, forming the glass and cooling it results in a plain, clear glass. But if the product is properly reheated, it turns ruby red as if by magic! That much has been know for centuries.

But in 1938 Dr. Dalton took a clear saucer made of glass containing copper, exposed it to ultraviolet rays and then reheated it. The result was a much deeper ruby red than usual. Then he found that by masking certain portions of glass and exposing the unmasked portion, ultraviolet light plus reheating produced colored patterns in the glass.

Opal-white glass is produced by the same kind of reheating process as ruby glass. Dr. S. Donald Stookey, curious about the photosensitive process, decided to try ultraviolet light in the hope of producing white images in clear glass. Nothing happened at first, until he discovered that it was a chemical change in copper that brought the change in Dalton's ruby red. And Stookey's opal glass had no copper in it. By changing his ingredients, Stookey got precise images of ruby red in opal-white glass. Then, going back to his hope of opal-white images in clear glass, he tried a double heat treatment and succeeded, getting a white image in clear glass.

Still curious, he wondered whether one portion of the glass was more quickly dissolved in acid than another. Trying one kind of glass after another and finally trying a glass that had once been rejected as unsatisfactory, he found the white images dissolved in acid much more quickly than did the clear glass. From this discovery has come the tremendous number of applications of electrical printed circuits on glass that have made miniature electronic systems possible for guided missiles, fine screens for electronic tubes with as many as 560,000 evenly spaced holes per square inch, among other applications.

One day Don Stookey was reheating a plate of his new kind of glass in a laboratory furnace. Suddenly the regulator went out of control and the temperature climbed 600 degrees higher than called for. Hours later Stookey discovered what had happened. He opened the door of the furnace expecting to see a pool of molten glass. To his surprise, the glass had turned brown, but it was still a solid plate. He was taking it out of the oven with a pair of tongs when it slipped and fell to the floor. With a metallic clang it bounced. But it didn't break! It was no longer glass, he found out later. It had changed to a ceramic that was harder and three times stronger than the parent glass!

From this tough new substance came Pyroceram, the material that is used in the nose cones of missiles that get terrifically hot (without ill effect) and in the tough ovenware that is pure white and won't break even if you take it from the oven and drop it in a bath of icewater.

New compositions of Pyroceram are as hard as the hardest steel. They can be used in hundreds of applications where very high heat must be withstood and hardness is required. Pyroceram can be transparent or opaque white, and because it is first a glass, it can be formed into any shape that glass will take, and by the same methods. Then with reheating it is transformed into a ceramic material.

Tempered glass is superior in strength to ordinary glass. But Corning has developed a glass that is far more resistant to breakage than the best of the tempered glass. They call it Chemcor, because it is a chemically treated glass made with a series of special-formula kinds of glass. One of them is the strong tableware you may have seen. Another is a thin glass used in the rear windows of convertible automobiles. Another is the glass used in the lenses of safety goggles.

Modern glass and glass ceramics are amazing. But there are more surprises in store for us, as you will see.

# 13. Glass in Your Workshop

NEARLY EVERYONE KNOWS SOMEBODY WITH skill in woodworking or metalworking, even though he may be an amateur. But do you know anybody who is a highly skilled amateur glassworker? Even the most experienced carpenters and cabinetmakers are inclined to make careful measurements when they have a broken window, and then call on a hardware dealer or building-supply house to cut a pane of glass. Ask them why, and they will probably say, "They have the tools" or "They do it every day." Both answers are good. But it is actually a simple job. Perhaps you'd like to know how to replace a window or to frame a photograph, or just to add another skill.

On a clean, flat cutting board that will support the full length of your cut, lay the glass with the line of the expected cut parallel to and near the edge of your board. Put a metal straight edge on the glass to guide your cutter. If you have a long cut to make, you will either have to devise some stops to prevent the straight edge from slipping, or else call on a helper to hold it steady. Put a little kerosene on the cutting wheel of your glass cutter to be sure it revolves easily. Now, with one firm, continous stroke, scratch the glass with your cutter from one side to the other. Next, move the glass so that the scratch will be parallel to, but just *off* the edge of the board. If you bend the glass now, it will break along the scratch. But for a *cleaner* break, wet the whole length of your scratch by running a wet finger along the line. Water, penetrating the crack, increases the effectiveness of the scratch and assures a good right-angle break. Old-timers at this job do it with bare hands. Before you break your glass, better play safe and slip on a pair of gloves. By the way, cutting new glass is much easier than cutting a piece of old, used glass that has been scratched and weathered: the old scratches can start a fracture that rays off into the wild blue yonder!

Every chemist has occasion to cut pieces of glass tubing. It is even simpler than cutting flat glass. But it is a good idea to use gloves when you do this, too. Ordinary tubing one-quarter inch in diameter is a usual size. Scratch a piece where you want it cut. The easiest scratching instrument is a triangular file, but any file will do; even a knife will serve, although glass is hard on the edge of the blade. Make your scratch across the tubing, at right angles to its length. Put your thumbs on each side of the scratch and break it by bending and pulling at the same time in one quick movement. The break should be clean, but it will probably have some sharp edges. So it is advisable to smooth off the sharp edges. How? A gas flame is the easiest answer. To avoid cracking the tube, heat the sharp end slowly by holding it near but not in the tip of the flame for a couple of seconds, rotating the tube slowly so the whole circumference is heated more or less evenly. Gradually bring the end of the tube into the flame, still rotating it, and keep it there just long enough so that the sharp end softens slightly and smoothes off. Set it aside to cool. Remember that glass doesn't conduct heat well, so that it is possible to hold one end of a six-inch length of tubing while the other end gets red hot. But remember, too, that it takes a surprisingly long time to cool off. So don't pick it up by the flamed end too soon; we wouldn't say "We told you so," but don't give anybody else reason to say so, either!

As a miniature sample of the gaffer's experience with a blowing iron, try making a bubble in the end of a piece of tubing. Handling the tubing in the flame in the same way you did to dull the sharp end, hold and roll the tubing until the end melts and flows together, closing the end completely. If you were to blow in the open end of the tubing while the glass is too hot, you would probably blow a hole right through it. So, let it cool off. Then reheat the sealed end of the tube and blow strongly into the open end to form a bubble.

The way in which thermometer tubing is made can be illustrated by heating an inch or so of the middle of a piece of small-diameter tubing in a flame. Roll the tubing in your fingers as usual in order to heat it evenly. When the center section is soft, pull both ends apart quickly. You will see that no matter how small the diameter of the piece in the center, it will still be hollow.

Is there a high temperature furnace at your school? If so you can make Prince Rupert drops, the tadpole-shaped drops you read about in Chapter 3.

For this experiment you will need some pieces of clean, broken glass, a crucible, goggles, a bucket, a battery jar (or heavy glass plate), pliers, and a hammer. Sounds like a lot of equipment, but you'll find the drops interesting enough to be worth the effort.

Place your pieces of glass in a crucible and heat them to 1350° to 1450° C. At that temperature the glass will be fluid. With a small ladle, or with tongs holding a small crucible, pour separate gobs of the molten glass into a bucket of cold water. Now put on your goggles. Try hammering the body of the drop. It won't break! *But* put the glass teardrop-shape with a tail into a battery jar or hold it behind a glass plate, and with your pliers twist off the tip of the tail. The whole drop will explode or disintegrate! If your friends don't know about them, like English King Charles II of old they may think it is all done by magic.

The bend in any curved glass tubing should have the same inside diameter as the straight sections, or the flow of fluid will naturally be restricted. Bending a tube with this object in mind is not difficult. Put a stopper in one end of a straight piece of tubing. Hold the closed end in one hand and, rolling the center section in the flame, heat as long a section as you need for the kind of bend you plan. Naturally, a full U-bend will take a longer heated section than a simple forty-five or ninety-degree bend. When the section becomes soft enough, take it quickly from the flame and bend it to the curve you wish. Then blow into the open end with enough pressure to straighten out any irregularities and to expand the inside diameter of the curved section to the extent required. Don't blow into the tube before bending or you may do one of two things: either blow a hole in the wall of the very soft glass, or bulge it in the softest part of the heated glass, which may not be where you want a bulge at all.

How good are you at artistic design? You can make an interesting pattern on a piece of flat glass, and you do not need to work with acids, which are difficult to handle. First, clean the surface of your glass and, having decided on your design, paint it on the glass with a good wood glue. Then set it aside to dry. As the glue shrinks it will tear off pieces of glass from the surface, each one shaped like an oyster shell, leaving a translucent pattern wherever you put the glue.

Here is a note on ordinary window glass. In spite of the vast improvements that have been made in manufacturing window glass, you will occasionally see pieces even today that have little waves and ripples that can distort the view beyond. But luckily, the ripples are likely to run in just one direction, and this will allow you to cut the glass in such a way that you can minimize the distorting effect. Cut the glass so that the ripples are horizontal if you are putting the glass in a window that you will see most frequently while walking past it, as in a hallway. But if you have a window at the head of a stairway that you approach while climbing upward, you will want the ripples running from top to bottom, so that the distortion will be least noticeable. So set the glass accordingly.

Have you some bottles, that used to have ground glass stoppers? Sometimes they get mixed up and you never do find the right stopper for the right bottle. Or old stoppers are saved when a bottle is broken, and usually you can find a stopper that is *nearly* the right size. If you find one that is just too big, you can grind it to a precision fit very easily. Your hardware store has, or will get you, coarse and fine carborundum powder for rough grinding and finishing. Mix some coarse powder with a paste made of flour and water so that it won't run away while you are working. Spread some on the stopper and turn the stopper back and forth in the neck of the bottle. Apply as much as you need to complete the rough job. Finish with the fine powder. If the package of powder at your hardware store is too big or too expensive, get some valve-grinding compound from your garage. A gob of it the size of the end of your little finger will do a lot of work if you don't waste it. A tiny can of it is surprisingly inexpensive.

Have you some glass with chipped edges you would like to smooth off? The way it is done in the factory is on a large grinding wheel that runs on a vertical axis and is constantly kept wet with a small jet of water. The speed is slow, and the grain of the wheel is relatively fine. Obviously you wouldn't try grinding glass with a large, high-speed, coarse-grain carborundum wheel: if the wheel didn't crack the glass by impact, it might crack it by uneven heating. But even at home without power tools it is an amazingly quick job to smooth off a relatively small nick with an ordinary carborundum stone that is intended primarily for sharpening knives or other tools with cutting edges. This smoothing can be done with either a wet or dry stone, and if you have one with coarse and fine faces, each can be used in turn. Final grinding can be done with emery cloth. If you are a perfectionist you can polish with emery powder on felt, backed with a wooden block.

Do you want to bore a hole in glass for an electric wire or for fastening a piece of plate glass to a wall with screws? It can be done with a special, spade-shaped drill made with a carbide tip. If it is used in a drill press (to prevent cracking the glass by moving the drill out of line), keep oil on the spot you drill. Be sure to keep a fairly light pressure on the glass to avoid cracking from heat or impact. If you are hanging a piece of glass or a mirror to the wall with screws, be sure to use a soft bushing between the hard metal screws and the glass, and a metal finishing washer under the head of the screw.

Do you have some fine glass that has been scratched or corroded? Depending on the depth of the scratching or corrosion, carborundum or emery powders of various grades can be used before final polishing with fine emery powder and felt. But a note of warning: antique glass can be more valuable in its corroded or scratched condition than it would be if refinished . . . all because of the fashion of the times and the genuine love of antiques.

If you know anyone in your community who has a kiln for ceramics, you can probably persuade them to put some glass pieces in the kiln the next time they are firing clay. What for? To fuse different pieces of colored glass together in an interesting art form.

Priscilla Porter of Washington, Connecticut, does some fascinating fused-glass work. Examples of her art are being sold from coast to coast. One example is a piece of light green glass in the shape of a fish. It has a gleaming dark blue eye of glass, too. It looks far simpler than it is when you watch her make it. On a cutting board she uses a wheeled cutting tool to scratch the outline of the fish on her light green glass. She does it with two or three deft motions. These scratches are not straight lines such as you use on window glass. So, to break the glass away from her fish outline, she uses a special pair of glass-cutter's pliers. If the break doesn't follow her scratches exactly, she uses the pliers to chew off little bits of the edge to even up the line. Then, with the same kind of glass but in a dark blue color, she cuts a small circle of the right size for the eye. Next she puts both pieces of glass in a kiln (with dozens of other pieces that she has prepared), the eye positioned correctly. In layers first of refractory slabs and then pieces of glass, they are stacked up, one on top of another.

Then the temperature control is set for the fusing temperature of the particular kind of glass she is using and the heat is turned on. (One kind of glass she frequently uses fuses at 1328° F. or 720° C.) After the glass has fused, the heat is turned off and the entire kiln is allowed to cool gradually. It doesn't take a full year the way the 200-inch telescope mirror blank for the Hale Telescope did. But it does take twelve hours or more. When the glass is taken out of the kiln, the green of the fish and the blue of the eye are fused together, almost as much one piece of glass as if they had come out of the same melting pot together at the start. Stars, animals, angels—almost anything you can imagine in this low-relief form of art—can be cut and fused together in beautiful translucent colors.

# 14. What Will They Think Of Next?

WHEN YOU KNOW THAT "FRAGILE" GLASS CAN be made so tough that you can set a dish of it on a block of ice and fill it with molten metal without breaking it; when you know that the same stuff they use for insulators on 100,000-volt power lines can be converted to *carry* electricity instead of insulating against it; when you know that the material you think of as transparent can have its transparency ignored because some other of its virtues are more important for special purposes, such as the enormous mirror blank for the Hale Telescope, you have very good reason to ask, "What will they think of next?"

In this chapter you'll learn some things few people know about glass. Yet they have already been put to work. Even more surprising are things glass experts have only clues to, are working on, and fully expect to produce.

In 1942 the armed forces wanted extremely thin glass to substitute for mica in electronic uses because mica from India was difficult to get in World War II.

When you pull molten glass from a tank, it is like pulling taffy or chewing gum: you increase its length but you decrease its width and its thickness. To make a thin ribbon only a thousandth of an inch thick and an inch wide, it looked as though glassmakers would have to start pulling it from a slot several feet wide—something that would set up fantastically difficult problems. Donald L. Brown, a chemical engineer, and Dr. Gail P. Smith at Corning Research found an answer in less than a year. They countered the natural flow of glass in one direction by a device at the slot of the tank opening, and produced a ribbon of glass so thin that it could be wound up on spools for delivery to the electronics manufacturers. Today this form of glass is being used in many applications from television to guided missiles.

There is a new way of seeing—not just around *the* corner but around as many curves as you can twist into a flexible tube-like device called a fiberscope. The technique is called fiber optics. The essential parts are incredibly fine fibers of optical glass packed together into a carefully arranged pipeline with rectangular ends so arranged that the top left and bottom right and every other one of 30,000 fibers at one end is in exactly the same position at the other end of the pipeline. Point one end of the pipeline at a subject and an image of it appears at the other end. Each one of the fibers has picked up light from the subject and faithfully carried this tiny dot of light or shade around curves and corners to the other end where it creates a complete mosaic to form the image.

The principle is an old one: when light passes through a transparent medium such as water or glass, if it strikes the surface at a particular angle it bounces back instead of going through. In fiber optics, each fiber is composed of two kinds of glass: a core of one kind and a covering of another kind, with a different index of refraction. The way this is done is to start with a glass tube of one index of refraction into which a rod of glass of another index fits very closely. A convenient size is a tube and rod about one inch in diameter. This is then heated to the right temperature for drawing, and the one-inch combination is pulled out to such a length that it is reduced to about one *thousandth* of an inch in diameter.

The result is an almost perfect internal mirror in which light is bounced back and forth the full length of the fiber much as a bullet would ricochet through a spiral of steel tubing (assuming, of course, that it couldn't break through). These fiberscopes are used in medicine, in the inspection of missile fueling, of boiler pipes and dozens of other hard-to-see spots. "Light pipes," in which the fibers do not have to end up in the same relative positions as at the start, are used for lighting difficult surgery, for instrument panels, in fire detection and data processing, and for many other purposes.

American Optical Company, among the first to market the fiberscope, makes a variety of sizes from seven-tenths of an inch in diameter and two feet long and larger.

When your automobile suddenly enters a dimly lit tunnel on a brilliant sunny day, your eyes have a major adjustment to make to see exactly where you are going. Normal eyes do it quickly, but it is always a shock, and if the adjustment is not quick enough, it can lead to an accident. But windshields may one day be made of glass that automatically transmits a greater proportion of the available light in the dark tunnel and less light in the brilliant sun to make such quick changes easier and safer. Window glass is already made that changes its light transmission when the sun goes under a cloud and again when the cloud sails away. Such windows have been installed in various buildings for testing, but as yet the reaction is a bit too slow to be practical in automobile windshields or in sunglasses.

The glass in your house can replace lamps and those useful but sometimes unsightly radiators, and do a triple job: it can transmit light in daytime, create light at night and at the same time keep your house warm. All this can be done with a glass that conducts electricity. On its surface it has a microscopically thin film of metal oxide, so thin that only an expert can tell it is there. It is this film that conducts electricity. From fifteen to twenty millionths of an inch thick, it is as durable as the glass itself. It doesn't interfere with the transparency of the glass. You can clean the surface as readily and harmlessly as you can clean the glass, without any special tools, chemicals or unusual methods.

When electricity flows through this film, the glass grows warm, and thermostats can control its temperature all the way up to the heat available in the oven in your kitchen. When the sun goes down, you can turn another switch and the same window that let in the light in the daytime will now glow with softly diffused light. This is achieved through another microscopically thin film, this one of phosphor. Different phosphors glow in blue, blue-green, green and yellow light. When scientists have developed one that produces a red glow, they'll be able to make glass glow with almost any desired color. Perhaps mirrors, windows, or whole ceilings of glass will be both heaters and sources of light in the houses of the future.

If you live in a part of the country where summer heat is a real problem, you will welcome the gray or cool blue-green glass that is designed to exclude a high percentage of the sun's radiated heat. Placed in south and west windows exposed to direct rays of the sun, glass like this keeps houses cooler and cuts the cost of air-conditioning.

You have read about the incredible tensile strength of single fibers of glass, strength that all too rapidly fades away to a tiny fraction of its original value. When you know what scientists have done with glass since the turn of the century, you can be sure they will find ways to make glass one of the leading structural materials of the world. The problem is to make it pliant enough to give under stress. It's hard to imagine glass as pliable as a plastic squeeze bottle yet stronger than steel. But researchers are constantly working on the hope that lightweight, inexpensive glass can someday give us lighter automobiles, trains, bridges, buildings and ships, the parts of which are fused together without nails or bolts or rivets.

Perhaps someday a malleable glass (there is no such thing today) will be developed that has the workability of plastic and the heat resistance of glass. A flexible glass with its chemical resistance may even replace damaged parts of the human body.

Toward such goals, researchers are earnestly striving. One example is a research program at Libbey-Owens-Ford Glass Company in Toledo, Ohio. There, scientists have intentionally broken $250,000 worth of perfectly good glass to find out how much pressure glass will actually stand in practice, as well as in mathematical theory.

Even more startling is the superserious proposal of H. A. Perry of the U. S. Naval Ordnance Laboratory to make deep-sea submarine vehicles of glass. The laboratory began investigating this possibility in 1963. Glass has extremely high load-bearing ability, and to overcome its weakness in "fracture toughness," the laboratory has proposed making spherical shells like inside-out safety-glass automobile windshields. This would be a sandwich with tough, fracture-resistant plastic outside a glass sphere and also inside it. In other words, glass would be the filling in the sandwich. Both plastic and glass are transparent and would make visible inspection of such a sphere possible both before and during diving, warning the crew to surface before a failure and disastrous break. (Steel or any other nontransparent material would have to be examined by X-ray before diving, and any defects that might develop could not be seen during a dive.) A buoyant spherical hull model ten inches in diameter and fitted with a circular hatch has been tested to a depth of 21,000 feet without leakage. Perhaps the ocean floors at the greatest depth known will someday be explored by men in a transparent workboat. Already in the planning stage, the first cabin would be eight feet in diameter.

From the day that an extremely delicate eye operation was performed at a New York hospital using light instead of older surgical techniques, the word "laser" has become better known to the general public as well as to scientists. What is a laser? It is a device that emits a single kind of light of just one wavelength in a narrow, intense beam. The rays are so nearly parallel that with a lens system its light may spread as little as one third of an inch per mile. That is about 10,000 times better concentration of light than the best searchlight ever made. The word "laser" is made up of the initial letters of the words of a descriptive phrase: "light amplification by stimulated emission of radiation." That needs some explanation, of course. Here it is.

As you have read, ordinary light is composed of many different wavelengths and radiates in every direction from any source—that is, any *ordinary* source. Obviously, the laser is not an ordinary source.

The principle of the laser is that when the atoms of certain materials are excited to a very high energy state, they return to their normal state by throwing off their excess energy as photons of light. The laser is made in such a way that it causes these photons to be shot out as one single kind of light with every wave in step with the one before and after it. Such a wave train can be modulated like that of radio, to carry a picture or sound. If it is used for this purpose, literally millions of television channels are available in the narrow band of visible light.

But there are hundreds of possible applications of the laser in addition to those of communications. Computers, fine measurements, satellite tracking, range finding, metal cutting and welding as well as medicine can all benefit from its use.

The first material used in making the laser was a rod of synthetic ruby. If the parallel ends of the rod are polished and silvered and ordinary light is shot into one end through a semitransparent silvering, the light bounces back and forth from end to end, exciting the atoms of the ruby structure to the point where they are so energized that they eject their excess energy in a burst of a single-wavelength light.

The material of one laser used in eye surgery was not the ruby but a special kind of glass. This glass is a pale violet color that contains neodymium, one of the so-called rare earths. Until this glass was used for the laser, it was chiefly used for its color in art glass. In the laser, glass is cheaper and more efficient than ruby; it can also be made in any shape and can be made more homogeneous than ruby.

There are several other forms of lasers using gases and liquids as well as solids. The development of all of them will be fascinating to watch.

An early stunt that indicated the possibilities of lasers was one conducted by the Massachusetts Institute of Technology and the Raytheon Company. Through a telescope, they bounced and received a light pulse off the moon. The laser beam was so narrow that its light on the moon was less than two miles in diameter, 100 times narrower than the smallest radar beam ever produced. This means, of course, that the power of the beam is concentrated into a far smaller circle than the radar beam. As a consequence, it can be aimed at any target far more accurately and with far greater strength in relation to the power that goes into its production. As an illustration of its accuracy, early in the development of the laser, Hughes Aircraft developed a forty-five-pound gunlike range finder that was accurate within fifteen feet on a target from seven to fifteen miles away.

Fascinating as such things are, the future of glass itself is far more so. In fact, the officially accepted definition of glass that specifies that it is a "fused" material may have to be changed one day. For scientists have found a kind of sponge from the very deep sea that, like the radiolaria mentioned in a previous chapter, have needle-like parts of true glass in their makeup. These were made by nature in the cold, high pressure of deep salt water and were never fused at all!

This fact opens up one of the most interesting fields of glass research. New knowledge along these lines can cause a revolution if the scientists find the answer they are seeking. Perhaps they will invent a way to make glass with enzymes plus the high pressures found at 20,000 feet under the sea instead of in furnaces at terrific heat.

Such a step must be thought of as a tremendous leap into the future. But when we consider the vast distance glass has come in the relatively short time since the beginning of this, our own century, nothing seems impossible.

Glass, with its many unique qualities and its countless uses, is one of today's miracle materials. Yet it promises even greater achievements in tomorrow's world.

# Glossary

*Acid-polish*—Process of diminishing scratches by dipping finished glass in acid.

*Annealing*—Reheating and cooling glass under careful controls to remove any stresses that have been produced within the glass as it was formed. In machine manufacture, glassware that has been formed is placed on moving belts that go into a tunnel where the glass is reheated and then slowly cooled.

*Bait*—A metal object, usually iron, that is lowered into molten glass in order to make it stick so that it can be withdrawn as a long ribbon for further forming.

*Batch*—The mixture of cullet and raw materials for glass to be fed into a tank or a pot for melting.

*Blank*—A piece of glass that is roughly the shape of its future form. The blank for a lens of eyeglasses, for example, may be three or three and a half inches in diameter.

*Blowmold*—A metal mold that is used to shape a glass article by blowing molten glass within it.

*Blowpipe*—A long metal tube. By gathering molten glass on one end and blowing into the other, a glassblower makes a bubble and then expands and shapes it into the finished article. The blowpipe has a pear-shaped knob at one end and the mouthpiece at the other.

*Cane*—Solid glass rod used in "lampwork" with glass tubing to make a variety of articles, from glass menageries to the most intricate kinds of laboratory equipment. Canes are drawn by machines at extremely high speed.

*Charge*—The batch of material that is fed to the furnace for melting.

*Chipped glass*—Glass that is chipped by the action of glue that has been applied to it in order to create a design on its surface.

*Continuous tank*—A glass tank in a furnace in which raw materials are charged in one end and finished molten glass is removed from the other. The level of the glass remains the same at all times through the constant feed of raw materials to replace the glass withdrawn.

*Crown glass*—Flat glass that is made by blowing a bubble on the end of the blowpipe, cutting a hole in the bubble diametrically opposite the point of attachment of glass and pipe, and then rotating both pipe and bubble rapidly so that the bubble flattens into a disk by centrifugal force. Also, a glass made with silica, potassium, sodium and barium oxides.

*Crucible*—A dish or pot made of a refractory material (difficult to melt) used for melting any other materials at high temperature.

*Crystal*—Any material that has a definite, regular internal structure. Transparent quartz of gem quality is crystalline, and because some fine glass has the brilliance and transparency that comes close to that of the gem, it has been called "crystal glass." But glass is *not* crystalline. See Chapter 7.

*Cullet*—Scrap glass (usually of the same kind as that to be melted) which is added to the raw materials of glass as scrap iron is used in iron or steel melting.

*Cut Glass*—Glassware that has been decorated by grinding patterns on its surface with grinding wheels, and then polished.

*Dispersion*—The division of white light into its component colors by glass or other means. See Chapter 11.

*Emery*—A polishing powder which is a compound of aluminum plus some impurities that give it its characteristic color.

*Engraving*—Cutting designs by use of small cutting wheels or hand tools.

*Enzymes*—Complex substances found in plants and animals which are capable of bringing about chemical reactions in other substances by catalytic action, which means that the enzymes themselves are not transformed or changed.

*Etched glass*—Glass that has been decorated by chemical action of acid. Glass is first covered with acid-resistant wax. The wax is then cut away with a sharp instrument wherever the lines of the design are to appear. Acid is then used to etch the glass, and, when deep enough, the acid is washed off and the wax removed.

*Fiber*—A filament of glass made by drawing molten glass through extremely fine holes of a spinneret, which see.

*Fining*—See Plaining.

*Fire-polish*—Polishing glass by flame played on its surface. This is part of the "float-glass" method of making plate glass.

*Flat glass*—Any one of these: window glass, plate glass, rolled glass that may be figured, translucent, etc.

*Flint glass*—This is *not* made of flint, though flint gave its name to it when the English first made beautifully sparkling glass with lead. Originally they *did* use ground flint instead of ordinary sand. Today the name has stuck to glass that is very dense because of a high lead content. It is used for the finest art glass and finest tableware.

*Float glass*—Plate glass made by feeding the ribbon of molten glass from a continuous furnace onto the surface of a shallow trough of molten tin, where it floats and forms a level, smooth bottom surface. The top surface is fire-polished.

*Fuse*—To join or blend by melting with heat.

*Gaffer*—The head of a shop (which see). He is a master glassblower, is responsible for the quality of the work, and usually does the most difficult operations himself.

*Gather*—A gob or ball of molten glass taken from the top of a pot or tank on the end of a blowpipe or pontil.

*Glass*—An inorganic substance usually transparent or translucent, the product of fusion, and cooled to a rigid condition without crystallizing. It usually consists of a solution of silicates, and may be colored, colorless and all degrees from transparent to completely opaque.

*Glassblowing*—The shaping of glass by air pressure, either by mouth or by machine.

*Glass tank*—The container for raw materials and molten glass within the glass furnace. It is made of refractory (which see) blocks.

*Glaze*—A smooth, shiny surface. It may or may not be glass, depending on the materials of which it is made, and how it is made.

*Gob*—Molten glass gathered on the end of a blowpipe or pontil or a portion of molten glass delivered by an automatic feeder from the furnace to the tools for forming.

*Heat-absorbing glass*—Glass specially made to exclude infrared (heat) rays.

*Heat-resistant glass*—Glass able to resist great thermal changes without breaking. It resists breakage because it is so made that it expands and contracts extremely small amounts as the temperature goes up and down.

*Laminated glass*—See *Safety glass.*

*Malleable*—When a material, especially metal, can be hammered into form or rolled into thin sheets without cracking, it is said to be malleable. Gold is considered to be the most malleable of metals.

*Marvering*—The process of rolling a gob on an iron slab to shape it, and at the same time, by cooling, to permit the glass to form an outside skin that is thicker than the molten glass within.

*Melt*—A quantity of glass made at one time.

*Metal*—A quantity of molten glass is sometimes referred to as though it were molten metal. The word is not used in this sense in this book.

*Mold*—A form used to shape glass. Usually made of metal, it can be plain or lined with a lubricant.

*Mold-blown glass*—The partially formed bubble of glass from the blowpipe or automatic machine is dropped into a mold where air pressure expands it to complete its formation.

*Mold mark*—The mark left on glass by the joining of two or more parts of a hinged mold.

*Natron*—Native soda.

*Obsidian*—Natural glass made by volcanic action.

*Offhand process*—The blowpipe method of making glass articles that are either not possible by machine methods, or are desired in such small quantities that machine methods are not economical.

*Optical glass*—Glass made for optical instruments and cameras. It must be as free as possible of color and must be homogeneous to be of good quality.

*Parison*—The initial stages of a bubble of glass which is to be formed into a glass article.

*Paste mold*—Any mold, usually metal, that is lined with a paste of soap, resin or beeswax. The lining is kept wet so that any rotating glass article being formed revolves on a cushion of steam made by contact of the hot glass on the wet lining.

*Photosensitive glass*—This makes possible the printing of photographic images in the glass by exposure to ultraviolet light, followed by a heat treatment. The image is as permanent as the glass itself.

*Plaining*—The final process in the pot or tank furnace, which permits the removal of bubbles before the molten glass is taken out for forming.

*Plate glass*—A high-quality flat glass made in the older method by casting or rolling molten glass, grinding the cold glass with sand and polishing on both sides; or in the newer method called "float glass," which see in this glossary.

*Pontil*—An iron rod used for gathering glass gobs and for attaching to portions of glass for further manipulation after the article has been separated from the blowpipe. (Called a "punty.")

*Pot*—A refractory container used for melting the materials of glass.

*Press and blow*—A method in which both pressing and blowing are used in the formation of glass articles. The first forming is usually by pressing and the final by blowing.

*Pressed glass*—Glass that has been formed by dropping molten glass into a mold in which its shape and surface design is imparted by the action of a plunger forcing the molten glass against the mold surface, which may be either plain or modeled.

*Pumice*—A natural volcanic glass froth of hard, spongy texture. It is used for smoothing and polishing.

*Punty*—Another name for pontil, which see.

*Pyrex*—The trade name for borosilicate glass widely used in heat-resistant wares for kitchen and laboratory.

*Refractory*—"Hard to melt" is the meaning of the word, and refers to pot and tank materials used in making pots and furnace linings for melting glass (and metals.)

*Ribbon machine*—One in which molten glass is delivered in ribbon form to the forming tools of the machine.

*Rouge*—Iron oxide, commonly used in the final operation of any glass manufacture in which a high polish is required.

*Safety glass*—A sandwich of two pieces of glass cemented together with heat and pressure by the plastic filling in the sandwich. It is this plastic core that holds the fragments of glass together in event of breakage.

*Sand*—A rock material of granular form that is coarser than dust but finer than gravel. Sand used for glass is mostly $SiO_2$ (silica) and is found as a sandstone which has to be ground, or in banks of loose sand.

*Sandblasting*—Blowing of sharp, abrasive sand against the surface of glass to give it a rough texture and to make it translucent instead of transparent.

*Sandwich glass*—Glass (early American) made by the Boston and Sandwich Glass Company of Sandwich, Massachusetts.

*Seam*—The mark on the surface of glass caused by the meeting of two or more parts of hinged molds in which the glass was formed.

*Seeds*—Imperfections in glass caused by incomplete melting of the materials.

*Shop*—A group of five to seven men who work together as a team in the hand production of glassware. See Gaffer.

*Soda-lime-silica glass*—The oldest and still the most widely used type of glass. Melted in huge quantities in large tanks, it is the glass commonly used for low-cost bottles and food containers.

*Spall*—The verb used to indicate the powdering or crumbling of brick as it disintegrates.

*Spinneret*—The metal or ceramic nozzle used to extrude fibers of glass. Originally developed for use in extruding fibers of rayon, it was adapted for use with molten glass. It can contain dozens of holes.

*Stained glass*—Windows made with pieces of colored glass that has been manufactured as colored glass, or with glass that has actually been stained with a color on its surface and usually fired after the staining.

*Stones*—Solid particles that remain undissolved in the molten glass. In finished products they are flaws that distort or obscure transparency.

*Stress*—A condition of tension or compression. Incomplete annealing is the cause of stress in finished glass at room temperature, while heating or cooling invariably causes stress to greater or less degree according to conditions.

*Tempered glass*—A strong glass made by cooling it rapidly from a temperature near its softening point.

*Tensile strength*—The strength of a material under the stress of pulling or stretching.

*Thermal endurance*—The ability of glassware to stand the shock of sudden temperature changes.

*Translucent glass*—Glass through which objects cannot be clearly seen. Microscopic, colorless particles bend light rays at all angles, diffusing light and blurring or completely obscuring objects on the side opposite the viewer.

*Transparent glass*—Glass that permits the light to pass freely without great scattering or absorption so that objects can be seen through the glass.

*Viscosity*—The resistance to the flow of a liquid or a molten material or the resistance to movement of a solid material through it. One measure of viscosity is the length of time it takes for a steel ball to fall through a given distance within a liquid. The greater the time, the greater the viscosity of the liquid.

*Vitreous*—From the Latin word for glass, *vitrum*. This word means “like glass,” resembling glass in some way, or looking like glass.

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The team of Ellsworth Newcomb and Hugh Kenny is a rare example of perfect professional collaboration between husband and wife. They have worked together on many stories and articles and on a number of books, including Miracle Plastics, Miracle Fabrics, Miracle Metals, and Alchemy to Atoms, all written for Putnam's.

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